

VISIT...

LANZAROTE
Caliente.COM

SECTION 15

DIRECT CURRENT POWER TRANSMISSION

Michael P. Bahrman

ABB, Inc.

CONTENTS

15.1	INTRODUCTION	15-1
15.2	APPLICATIONS	15-4
15.3	HVDC FUNDAMENTALS	15-5
15.3.1	Converter Behavior and Equations	15-5
15.3.2	Station Layout and System Configuration	15-8
15.3.3	Reactive Power Compensation	15-11
15.3.4	Control and Operation of HVDC Links	15-11
15.3.5	Multiterminal Operation	15-14
15.3.6	Economics and Efficiency	15-15
15.4	ALTERNATIVE CONFIGURATIONS	15-16
15.4.1	Capacitor-Commutated Converters	15-16
15.4.2	Grid Power Flow Controller	15-17
15.4.3	Variable Frequency Transformer (VFT)	15-17
15.5	STATION DESIGN AND EQUIPMENT	15-17
15.5.1	Thyristor Valves	15-17
15.5.2	Converter Transformers	15-18
15.5.3	Smoothing Reactor	15-19
15.5.4	AC Filters	15-19
15.5.5	DC Filters	15-20
15.5.6	Power Line Carrier (PLC) Filters	15-20
15.5.7	Valve Cooling System	15-21
15.5.8	Reliability and Availability	15-21
15.6	VOLTAGE SOURCE CONVERTER (VSC) BASED HVDC TRANSMISSION	15-21
15.6.1	System Characteristics	15-21
15.6.2	Applications	15-22
15.6.3	VSC Station Configuration and Design	15-23
15.6.4	Converter Control	15-26
15.6.5	Pulse-Width Modulation (PWM) and Harmonic Generation	15-28
15.7	OVERHEAD LINES AND CABLES	15-30
15.7.1	Overhead Transmission Lines	15-30
15.7.2	Underground and Submarine Cables	15-31
15.7.3	Ground Electrodes	15-31
15.8	ULTRA-HIGH VOLTAGE DIRECT CURRENT (UHVDC) TRANSMISSION	15-34
	REFERENCES	15-34

15.1 INTRODUCTION

High voltage direct current (HVDC) transmission is widely recognized as being advantageous for long-distance, bulk-power delivery, asynchronous interconnections and long submarine cable crossings. HVDC lines and cables are less expensive and have lower losses than those for 3-phase ac transmission.

Typical HVDC lines utilize a bipolar configuration with two independent poles and are comparable to a double circuit ac line. Because of their controllability HVDC links offer firm capacity without limitation due to network congestion or loop flow on parallel paths. Higher power transfers are possible over longer distances with fewer lines with HVDC transmission than with ac transmission. Higher power transfers are possible without distance limitation to HVDC cables systems using fewer cables than with ac cable systems due to their charging current.

HVDC systems became practical and commercially viable with the advent of high voltage mercury-arc valves in the 1950s. Solid-state thyristor valves were introduced in the late 1960s, leading to simpler converter designs with lower operation and maintenance expenses and improved availability. In the late 1990s a number of newer converter technologies were introduced permitting wider use of HVDC transmission in applications, which might not otherwise be considered. A list of HVDC projects currently in operation or under construction is given in Table 15-1.

TABLE 15-1 HVDC Project List

Name of HVDC system	Year commissioned/ upgraded/ retired	Nominal capacity (MW)	DC voltage (kV)	B-B line/ cable (km)	Location
Under Construction					
ESTLINK	2006	350	150	106	Estonia-Finland
BASSLINK	2005	500	400	360	Australia
NORNED	2007	600	500	580	Norway-Netherlands
THREE GORGES-SHANGHAI	2007	3000	± 500	900	China
NEPTUNE	2007	600	500	102	U.S.A.
MISSION	2007	150	± 21	B-B	U.S.A.
Operational					
VANCOUVER 1	1968	312	+260	74	Canada
VOLGOGRAD-DONBASS	1962	720	± 400	470	Russia
SAKUMA	1965/1993	300	2×125	B-B	Japan
NEW ZEALAND HYBRID	1965/92	1240	+270/-350	612	New Zealand
PACIFIC INTERTIE	1970/84/89/02	3100	± 500	1361	U.S.A.
NELSON RIVER 1	1973/93	1854	+463/-500	890	Canada
GOTLAND HVDC LIGHT	1999	50	± 60	70	Sweden
DIRECTLINK	2000	3×60	± 80	59	Australia
MURRAYLINK	2002	200	± 150	176	Australia
CROSS SOUND	2002	330	± 150	40	U.S.A.
TROLL	2004	2×40	± 60	70	Norway
EEL RIVER	1972	320	2×80	B-B	Canada
VANCOUVER 2	1977	370	-280	74	Canada
DAVID A. HAMIL	1977	100	50	B-B	U.S.A.
SHIN-SHINANO 1	1977	300	125	B-B	Japan
SQUARE BUTTE	1977	500	± 250	749	U.S.A.
CAHORA-BASSA	1978	1920	± 533	1420	Mocambique-South Africa
C.U.	1979	1128	± 411	702	U.S.A.
ACARAY	1981	50	26	B-B	Paraguay
INGA-SHABA	1982	560	± 500	1700	Zaire
EDDY COUNTRY	1983	200	82	B-B	U.S.A.
CHATEAUGUAY	1984	2×500	2×140	B-B	Canada
BLACKWATER	1985	200	57	B-B	U.S.A.
HIGHGATE	1985	200	56	B-B	U.S.A.
MADAWASKA	1985	350	140	B-B	Canada
MILES CITY	1985	200	82	B-B	U.S.A.
OKLAUNION	1985	220	82	B-B	U.S.A.
BROKEN HILL	1986	40	$2 \times 17 (\pm 8,33)$	B-B	Australia
CROSS CHANNEL BP 1+2	1986	2000	± 270	71	France-U.K.

TABLE 15-1 HVDC Project List (*continued*)

Name of HVDC system	Year commissioned/ upgraded/ retired	Nominal capacity (MW)	DC voltage (kV)	B-B line/ cable (km)	Location
IPP (INTERMOUNTAIN)	1986	1920	±500	784	U.S.A.
ITAIPU 1	1986	3150	±600	796	Brazil
ITAIPU 2	1987	3150	±600	796	Brazil
URUGUAIANAI	1987	54	18	B-B	Brazil-Uruguay
VIRGINIA SMITH	1987	200	50	B-B	U.S.A.
FENNO-SKAN	1989	572	400	234	Finland-Sweden
McNEILL	1989	150	42	B-B	Canada
SILERU-BARSOOR	1989	100	±200	196	India
VINDHYACHAL	1989	500	2 × 69.7	B-B	India
RIHAND-DELHI	1992	1500	±500	814	India
SHIN-SHINANO 2	1992	300	125	B-B	Japan
BALTIC CABLE	1994	600	450	255	Sweden-Germany
KONTEK	1995	600	400	171	Denmark-Germany
WELSH	1995	600	162	B-B	U.S.A.
CHANDRAPUR-RAMAGUNDUM	1997	1000	2 × 205	B-B	India
CHANDRAPUR-PADGHE	1998	1500	±500	736	India
HAENAM-CHEJU	1998	300	±180	101	South Korea
LEYTE-LUZON	1998	440	350	443	Philippines
VIZAG 1	1998	500	205	B-B	India
MINAMI-FUKUMITZU	1999	300	125	B-B	Japan
KII CHANNEL	2000	1400	±250	102	Japan
SWEPOL LINK	2000	600	450	230	Sweden-Poland
GRITA	2001	500	400	313	Greece-Italy
HIGASHI-SHIMIZU	2001	300	125	B-B	Japan
MOYLE INTERCONNECTOR	2001	2 × 250	2 × 250	64	Scotland-N.Ireland
TIAN-GUANG	2001	1800	±500	960	China
THAILAND-MALAYSIA	2001	600	±300	110	Thailand-Malaysia
EAST-SOUTH INTERCONNECTOR	2003	2000	±500	1400	India
RAPID CITY TIE	2003	2 × 100	±13	B-B	U.S.A.
THREE GORGES CHANGZHOU	2003	3000	±500	890	China
GUI-GUANG	2004	3000	±500	936	China
THREE GORGES-GUANGDONG	2004	3000	±500	900	China
LAMAR	2005	211	±63	B-B	U.S.A.
VIZAG 2	2005	500	±88	B-B	India
KONTI-SKAN 1 AND 2	1965/88/2005	740	±285	150	Denmark-Sweden
SACOI	1967/85/93	300	±200	385	Italy-Corsica-Sardinia
SKAGERRAK 1-3	1976/77/93	1050	250/350	240	Norway-Denmark
NELSON RIVER 2	1978/85	2000	±500	940	Canada
HOKKAIDO-HONSHU	1979/80/93	600	±250	167	Japan
VYBORG	1981/82/84/02	4 × 355	1 × 170 (±85)	B-B	Russia-Finland
GOTLAND II-III	1983/87	260	150	98	Sweden
QUEBEC-NEW ENGLAND	1986/90/92	2250	±500	1500	Canada-U.S.A.
GESHA	1989/90	1200	±500	1046	China
GARABI 1&2	2000/02	2000	±70	B-B	Argentina-Brazil
RIVERA		70		B-B	Uruguay
SASARAM	2002	500	205	B-B	India
Retired					
KINGSNORTH	1972/1987	640		82	England
DUERNROHR 1	1983/1997	550	145	B-B	Austria-Czech
ETZENRIHT	1993/1997	600	160	B-B	Germany-Czech
VIENNA SOUTH-EAST	1993/1997	600	145	B-B	Austria-Hungary

15.2 APPLICATIONS

The significant increase in HVDC transmission can be attributed to one or more of the following reasons:

Economical. HVDC transmission systems often provide a more economical alternative to ac transmission for long-distance, bulk-power delivery from remote resources such as hydroelectric developments, mine-mouth power plants, or generation from large-scale wind farms. Whenever long-distance transmission is discussed, the concept of “breakeven distance” frequently arises. This is where the savings in line costs and lower capitalized cost of losses offsets the higher converter station costs. A bipolar HVDC line uses only two insulated sets of conductors rather than three. This results in narrower right-of-way (ROW), smaller transmission towers, and lower line losses than with ac lines of comparable capacity. A rough approximation of the savings in line construction is 30%. Although breakeven distance is influenced by the costs of ROW and line construction with a typical value of 500 km, the concept itself is misleading because in many cases more ac lines are needed to deliver the same power over the same distance due to system stability limitations. Furthermore, the long-distance ac lines usually require intermediate switching stations and reactive power compensation. For example, the generator outlet transmission alternative for the ± 250 kV, 500 MW Square Butte Project was two 345 kV series-compensated ac transmission lines. Similarly, the ± 500 kV, 1600 MW Intermountain Power Project (IPP) ac alternative comprised two 500 kV ac lines. The IPP takes advantage of the double circuit nature of the bipolar line and includes a 100% short-term and 50% continuous monopolar overload. The first 6000 MW stage of the transmission for the Three Gorges Project in China would have required 5×500 kV ac lines as opposed to $2 \times (\pm 500)$ kV, 3000 MW bipolar HVDC lines (Fig. 15-1).

For underground or submarine cable systems there is considerable savings in installed cable costs and cost of losses with HVDC transmission. Depending on the power level to be transmitted, these savings can offset the higher converter station costs at distances of 40 km or more. Furthermore, there is a rapid drop-off in cable capacity with ac transmission over distance due to the reactive component of charging current. Although this can be compensated by intermediate shunt compensation for underground cables, it is not practical to do so for submarine cables. For a given cable conductor area, the line losses with HVDC cables, can be less than half those of ac cables. This is due to more conductors, reactive component of current, skin effect, and induced currents in the cable sheath and armor.

Functional. The controllability and asynchronous nature of HVDC transmission provides a number of advantages for certain transmission applications. HVDC transmission capacity is firm and utilization usually runs higher due to its controllability. This is because congestion or loop flow on parallel transmission paths does not result in schedules curtailments for transmission loading relief.

With a cable system, unequal loadings or risk of postcontingency overloads often results in use of a series-connected phase-shifting transformer. These potential problems do not exist with a controlled HVDC cable system.

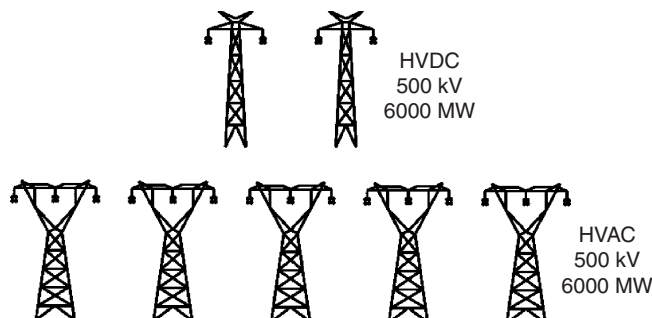


FIGURE 15-1 HVDC and EHV ac alternatives for first stage of three Gorges outlet transmission.

With HVDC transmission systems, interconnections can be made between asynchronous networks for more economic or reliable operation. The asynchronous interconnection allows interconnections of mutual benefit but provides a buffer between the two systems. Often these interconnections use back-to-back converters with no transmission line. The asynchronous links act as an effective “firewall” against propagation of cascading outages in one network from passing to another network. Many asynchronous interconnections exist in North America between the eastern and western interconnected systems, between the Electric Reliability Council of Texas (ERCOT) and its neighbors, that is, Mexico, Southwest Power Pool (SPP) and the western interconnect, and between Quebec and its neighbors, that is, New England and the Maritimes. The August 2003 northeast blackout provides an example of the firewall against cascading outages provided by asynchronous interconnections. As the outage propagated around the lower Great Lakes and through Ontario and New York, it stopped at the asynchronous interface with Quebec. Quebec was unaffected, the weak ac interconnections between New York and New England tripped, but the HVDC links from Quebec continued to deliver power to New England.

Environmental. HVDC allows delivery of more power over fewer lines with narrower ROW. This is especially important in trying to access diverse resources in remote locations where lines may pass through environmentally sensitive or scenic areas. There is no induction or alternating electromagnetic fields from HVDC transmission. There is no physical restriction limiting the distance for underground cables. Underground cables can be used on shared ROW with other utilities without impacting reliability concerns over use of common corridors. Lower cable losses improves efficiency and results in less heating in the earth.

15.3 HVDC FUNDAMENTALS

15.3.1 Converter Behavior and Equations

Conventional HVDC transmission schemes utilize line-commutated, current-source converters. Such converters require a synchronous voltage source in order to operate. The basic building block used for HVDC conversion is the 3-phase, full-wave bridge referred to as a 6-pulse or Graetz bridge (Fig. 15-2). The term 6-pulse is due to the characteristic harmonic ripple in the dc output voltage, which is at multiples of 6 times the fundamental frequency. Each 6-pulse bridge is comprised of 6 controlled switching elements or thyristor valves. Each valve comprises a number of series-connected thyristors to achieve the desired dc voltage rating.

Converter dc output voltage is controlled by means of a delayed firing angle. Valve switching is synchronized to the ac source voltages via a phase-locked loop. The bridge is coupled to the ac bus via a converter transformer. Commutation of converter currents from one phase to another results in a converter voltage drop. Converter voltage drop is proportional to transformer reactance and current level I_d , resulting in a reduction of the dc voltage level U_d due to commutation overlap u .

A set of equations has been derived to calculate U_d as a function of the phase voltages, the commutation reactance I_d , and the delay angle α . For rectifier operation converter polarity is positive, whereas for inverter operation it is negative bucking the direction of direct current flow. Equations describing inverter operation use extinction angle γ .

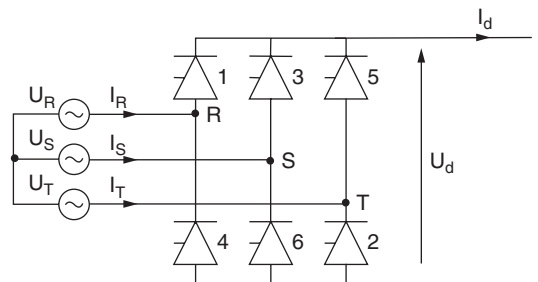


FIGURE 15-2 6-pulse bridge.

The direct voltage across the 6-pulse bridge is calculated by Eq. (15-1) for rectifier operation and Eq. (15-2) for inverter operation.

$$\frac{U_{dR}}{2} = U_{diOR} \cdot \left[\cos \alpha - (d_{xR} + d_{rR}) \frac{I_d}{I_{dN}} \frac{U_{diORN}}{U_{diOR}} \right] - U_T \quad (15-1)$$

$$\frac{U_{dI}}{2} = U_{diOI} \cdot \left[\cos \gamma - (d_{xI} - d_{rI}) \frac{I_d}{I_{dN}} \frac{U_{diOIN}}{U_{diOI}} \right] + U_T \quad (15-2)$$

The nominal relative inductive direct voltage drop is defined by Eq. (15-3), where X_l is the commutation reactance which includes the converter transformer reactance and any other reactances in the commutation circuit.

$$d_{xN} = \frac{3}{\pi} \frac{X_l \cdot I_{dN}}{U_{diON}} \quad (15-3)$$

The relative resistive direct voltage drop is defined by Eq. (15-4) where P_{cu} is the transformer and smoothing reactor load losses and R_{th} is current dependent voltage drop over the thyristors. The factor 2 is due to the fact that there are always two valves conducting at the same time.

$$d_r = \frac{P_{cu}}{U_{diON} \cdot I_{dN}} + \frac{2 \cdot R_{th} \cdot I_{dN}}{U_{diON}} \quad (15-4)$$

The overlap angle for the rectifier and inverter are described by Eqs. (15-5) and (15-6), respectively.

$$\cos(\alpha + \mu_R) = \cos \alpha - 2 \cdot d_{xNR} \frac{I_d}{I_{dN}} \frac{U_{diONR}}{U_{diOR}} \quad (15-5)$$

$$\cos(\gamma + \mu_I) = \cos \gamma - 2 \cdot d_{xNI} \frac{I_d}{I_{dN}} \frac{U_{diONI}}{U_{diOI}} \quad (15-6)$$

The reactive power consumption for a 12-pulse converter (two 6-pulse converters with 30° shift in valve voltages) connected in series is calculated with Eq. (15-7).

$$Q_d = 2 \cdot \chi \cdot I_d \cdot U_{diO} \quad (15-7)$$

where χ is the overlap function described by Eq. (15-8) for rectified operation and Eq. (15-9) for inverter operation.

$$\chi = \frac{1}{4} \cdot \frac{2 \cdot \mu + \sin 2\alpha - \sin 2(\alpha + \mu)}{\cos \alpha - \cos(\alpha + \mu)} \quad (15-8)$$

$$\chi = \frac{1}{4} \cdot \frac{2 \cdot \mu + \sin 2\gamma - \sin 2(\gamma + \mu)}{\cos \gamma - \cos(\gamma + \mu)} \quad (15-9)$$

The relationship between the no-load phase-phase ac voltage on the valve side and the ideal no-load direct voltage is shown in Eq. (15-10). The rms value of the rated ac current on the valve side of the converter transformer is shown in Eq. (15-11). The total rated MVA of the 3-phase transformer group feeding the 6-pulse converter bridge is according to Eq. (15-12).

$$U_{vo} = \frac{U_{diO}}{\sqrt{2}} \cdot \frac{\pi}{3} \quad (15-10)$$

$$I_{vN} = \sqrt{\frac{2}{3}} \cdot I_{dN} \quad (15-11)$$

$$S_N = \sqrt{3} \cdot U_{vN} \cdot I_{vN} = \frac{\pi}{3} \cdot U_{diON} \cdot I_{dN} \quad (15-12)$$

Figure 15-3 illustrates the commutation process and its effect on valve currents and dc voltage due to delay angle and overlap. The solid upper envelope of the phase voltages is the voltage top of the bridge

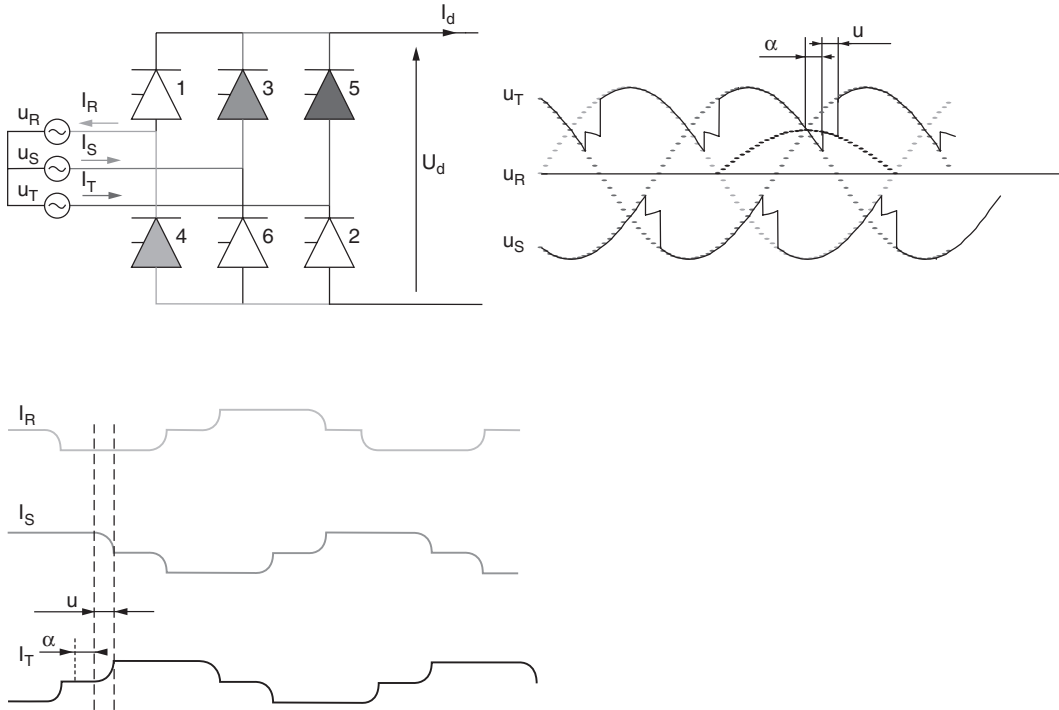


FIGURE 15-3 6-Pulse bridge commutation with delay angle and overlap.

with common valve cathodes, while the lower solid envelope is the voltage at the bottom of the bridge with the common valve anodes. The differential voltage across the bridge is the dc voltage U_d . The effect of the delay angle and commutation overlap on the dc voltage is evident. During commutation two valves in the same half bridge conduct simultaneously and the instantaneous voltage is half their sum.

The 6-pulse converter bridge can be used in rectifier operation with positive output voltage, $0 < \alpha < 90^\circ$, converting ac to dc or in inverter operation with an output voltage that is negative with respect to the direction of dc current flow, $90^\circ < \alpha < 180^\circ$. By connecting two converters in series at opposite ends of a transmission line, one controlling dc voltage and the other controlling dc current, dc power transmission is achieved. The characteristic current harmonics ($f = 6n \pm 1$) are filtered on the ac side and the characteristic voltage harmonics ($f = 6n$) are filtered on the dc side to meet voltage distortion and telephone interference requirements.

The dc terminals of two 6-pulse bridges with ac voltage sources phase displaced by 30° can be connected in series for 12-pulse operation. In 12-pulse operation, the characteristic current and voltage harmonics have frequencies of $12n \pm 1$ and $12n$, respectively. The 30° phase displacement can easily be achieved by feeding one bridge through a transformer with a wye-connected secondary and the other transformer through a delta-connected secondary (Fig. 15-4). Most modern HVDC transmission

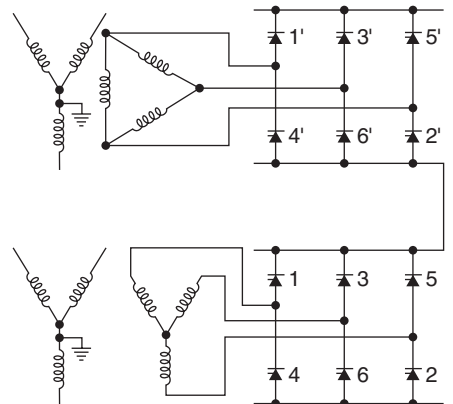


FIGURE 15-4 12-Pulse bridge.

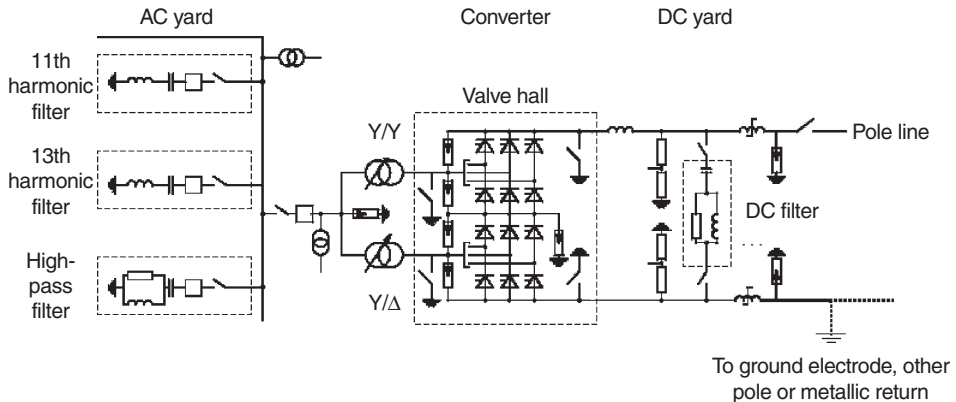


FIGURE 15-5 Simplified single line diagram for monopole.

schemes utilize 12-pulse converters to reduce the additional harmonic filtering requirements required for 6-pulse operation, for example, fifth and seventh on the ac side and sixth on the dc side. This is because although these harmonic currents still flow through the valves and the transformer windings, they are 180° out of phase and cancel out on the primary side.

15.3.2 Station Layout and System Configuration

A simplified single-line diagram for one pole with a 12-pulse converter is shown in Fig. 15-5. A CAD drawing and a photo of a monopolar converter station are shown in Figs. 15-6 and 15-7, respectively.

An HVDC converter station comprises the following major subsystems:

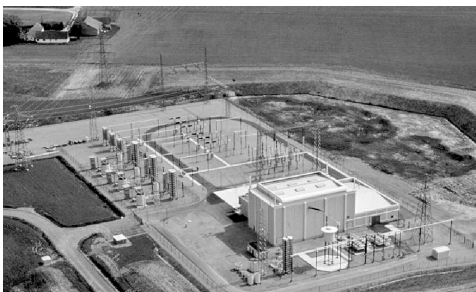


FIGURE 15-6 Monopolar converter station.

- Thyristor valves
- Converter transformers
- AC harmonic filters
- DC harmonic filters
- Valve cooling
- Control and protection
- Auxiliary power
- Valve hall building

The converter station layout depends on a number of factors such as the station configuration, that is, monopolar (Fig. 15-8), bipolar (Fig. 15-9) or back-to-back asynchronous tie

(Fig. 15-10), valve design, ac system interconnection, filtering requirements, reactive power compensation requirements, land availability, and the local environment. In most cases, the thyristor valves are air-insulated, water-cooled, and enclosed in a converter building often referred to as a valve hall. For back-to-back ties with their characteristically low dc voltage, thyristor valves can be housed in prefabricated electrical enclosures in which case a valve hall is not required.

To obtain a more compact station design and reduce the number of insulated high voltage wall bushings, converter transformers are often placed adjacent to the valve hall with valve winding bushings protruding through the building walls for connection to the valves. Double or quadruple valve structures housing valve modules are used within the valve hall. Valve arresters are located immediately adjacent to the valves. Indoor motor-operated grounding switches are used for personnel safety

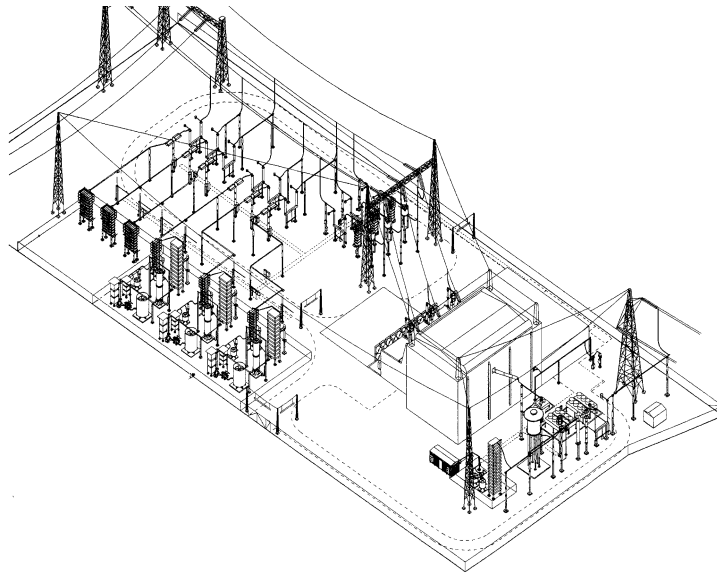


FIGURE 15-7 CAD drawing of monopolar converter station.

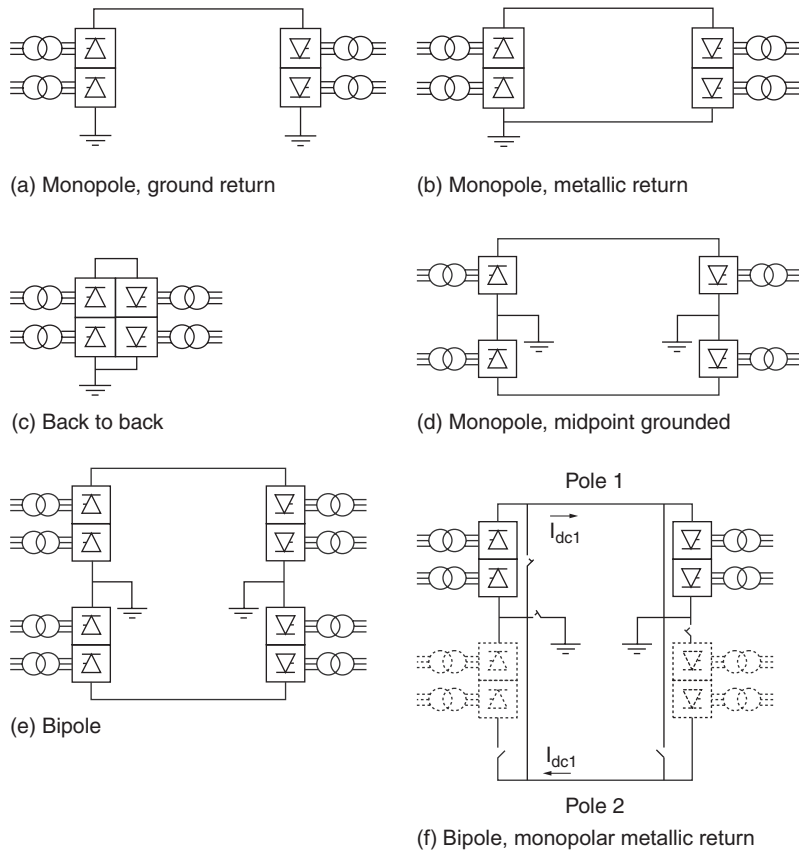


FIGURE 15-8 HVDC operating configurations/modes.

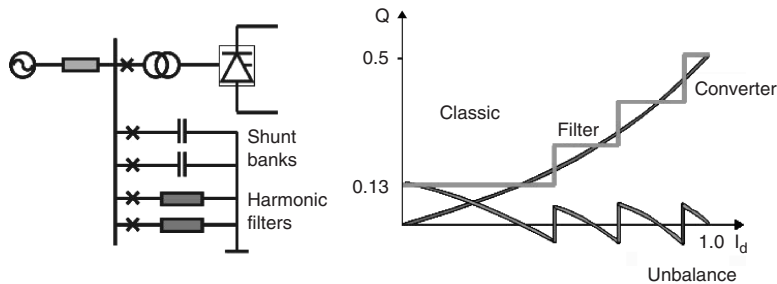


FIGURE 15-9 Reactive power balance.

during maintenance. Closed loop valve cooling systems are used to circulate the cooling medium through the indoor thyristor valves with heat transfer to dry coolers or evaporative cooling towers located outdoors.

Monopolar systems with ground return are the simplest and least expensive systems for moderate power transfers since only two converters and one insulated cable or line conductor is required. Such systems are commonly used with low voltage electrode lines and sea electrodes to carry the return current in submarine cable crossings.

In some areas conditions are not conducive to monopolar earth or sea return. This could be the case areas in heavily congested areas, fresh water cable crossings, or areas with high earth resistivities. In such cases a metallic neutral or low voltage cable is used for the return path and the dc circuit uses a simple ground local ground reference.

Back-to-back stations are used for interconnection of asynchronous networks and use ac lines to connect on either side. In such systems power transfer is limited by the relative capacities of the adjacent ac systems at the point of coupling.

As an economic alternative to a monopolar system with metallic return, the midpoint of a 12-pulse converter can be connected to earth directly or through an impedance and two half voltage cables or line conductors can be used. The converter is only operated in 12-pulse mode, so there is no earth current.

The most common configuration for modern overhead HVDC transmission lines is bipolar with a single 12-pulse converter for each pole at each terminal. This gives two independent dc circuits each capable of half capacity. For normal balanced operation there is no earth current. Monopolar earth return operation, often with overload capacity, can be used during outages of the opposite pole.

Earth return operation can be minimized during monopolar outages by using the opposite pole line for metallic return via pole/converter bypass switches at each end. This requires a metallic-return transfer breaker in the ground electrode line at one of the dc terminals to commutate the current from the relatively low resistance of the earth into that of the dc line conductor. Metallic return operation

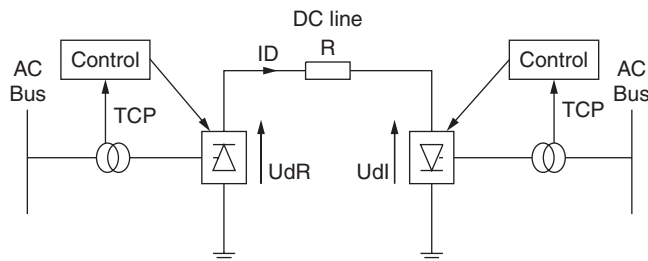


FIGURE 15-10 HVDC control system.

capability is provided for most dc transmission systems. This is not only effective during converter outages but also during line insulation failures where the remaining insulation strength is adequate to withstand the low resistive voltage drop in the metallic return path.

15.3.3 Reactive Power Compensation

As shown by Eqs. (15-7) through (15-9) in Sec. 15.3.1, HVDC conversion with line-commutated converters demands reactive power from the ac network at each HVDC terminal. The reactive power demand is a function of the firing angle in rectifier operation and extinction angle in inverter operation, the direct current and the overlap angle. The overlap angle is a function of the ac commutating voltage, the commutation reactance, and the dc current. As a rough approximation nominal reactive power demand at each terminal is about half the active power transfer.

The total reactive power produced by all the ac harmonic filters at each terminal is usually in the range of 30% to 40% of the converter rating. The filters therefore provide most of the reactive power compensation to meet the converter reactive power demand. The remaining reactive power necessary at the higher power levels can be provided from shunt capacitor banks, synchronous condensers, and static var compensators or nearby generation. Any reactive power mismatch must be provided or absorbed by the local ac system. Figure 15-9 shows the reactive power demand of a converter station, the reactive power from the filters, and the reactive power exchange with the ac network as a function of power transfer.

With weaker ac networks, that is, networks where the 3-phase symmetrical short circuit capacity is low compared to the rating of the dc converter station, various system constraints impact the reactive power compensation. With weaker systems, the size of the reactive power compensation elements may need to be reduced due to the voltage change on switching and the allowable reactive power exchange with the ac network. This may mean that filter banks may have to be subdivided with smaller branches. Sometimes, the minimum filtering requirements, for example, those at low power, exceed the reactive power demand of the converters, and shunt reactors are also required to absorb the excess vars from the filters.

15.3.4 Control and Operation of HVDC Links

The fundamental objectives of an HVDC control system are:

- To control basic system quantities such as dc line current, dc voltage, and transmitted power accurately and with sufficient speed of response
- To maintain adequate commutation margin in inverter operation so that the valves can recover their forward blocking capability after conduction before their voltage polarity reverses
- To control higher level quantities such as frequency in isolated mode or provide power oscillation damping to help stabilize the ac network
- To compensate of loss of a pole, a generator, or ac transmission circuit by rapid readjustment of power
- To ensure stable operation with reliable commutation in the presence of system disturbances
- To minimize system losses and reactive power consumption
- Ensure proper operation with fast and stable recoveries during system faults and disturbances

With HVDC transmission one terminal sets the dc voltage level, while the other regulates the dc current by controlling its output voltage relative to that maintained by the voltage-setting terminal. Since the dc line resistance is low, large changes in current and hence power can be made with relatively small changes in firing angle. Two independent methods exist for controlling the converter dc output voltage. These are (1) by changing the ratio between the direct voltage and the ac voltage by varying the delay angle α or (2) by changing the converter ac voltage via load tap changers (LTC) on the converter transformer. Although the former method is rapid, the latter method is slow due to

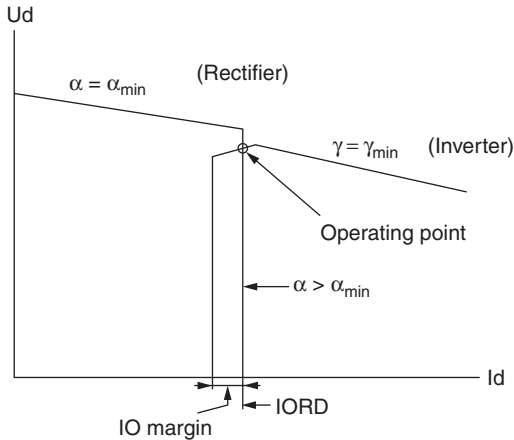


FIGURE 15-11 Static operating characteristics.

the limited speed of response of the LTC. Use of high delay angles to achieve a larger dynamic range, however, increases the converter reactive power consumption. To minimize the reactive power demand while still providing adequate dynamic control range and commutation margin, the LTC is used at the rectifier terminal to keep the delay angle within its desired steady-state range, for example, 13° to 18° , and at the inverter to keep the extinction angle γ within its desired range, for example, 17° to 20° , if the angle is used for dc voltage control or maintain rated dc voltage if operating in minimum commutation margin control mode.

Cooperation between the two terminals allows for efficient operation and provides for backup control modes for abrupt changes to the system voltages during disturbances. The converter control system at

each terminal provides a static control characteristic. The intersection of the static control characteristics at the rectifier and inverter terminals determines the operating point. With the rectifier operating in constant current control and the inverter in constant angle control, as shown in Fig. 15-11, presents a stable operating point.

Each converter terminal is equipped with a closed loop current control or current control amplifier (CCA) as shown in Fig. 15-12. The backup current regulator at the inverter comes into effect when the rectifier ac voltage is suddenly reduced, forcing the rectifier characteristic down resulting in a new operating point with the rectifier minimum firing angle setting the dc voltage and the inverter current order setting the current. This shift in operating point is referred to a mode shift. A dc voltage regulator may also be used with or without current compounding to achieve a positive slope at the inverter with minimum extinction angle or commutation margin as a backup. A mode shift can also occur for a sudden increase in inverter ac voltage if operating in constant extinction angle control.

Other control functions are needed to synchronize the valve firing to the ac system commutation voltages, to clear and recover from dc line faults, to translate the alpha orders to firing pulses and

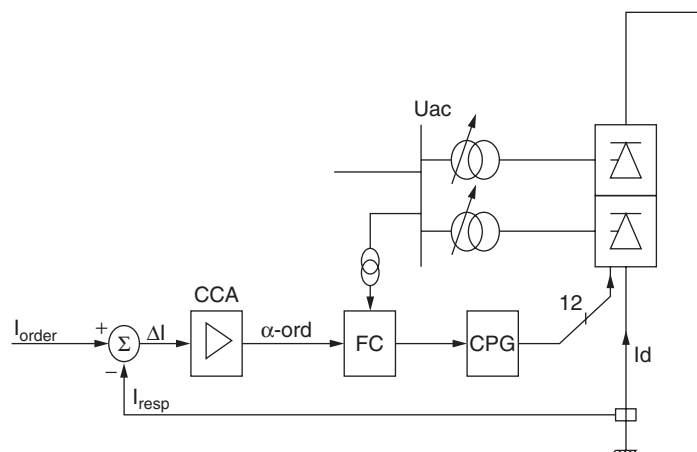


FIGURE 15-12 Closed loop current control system.

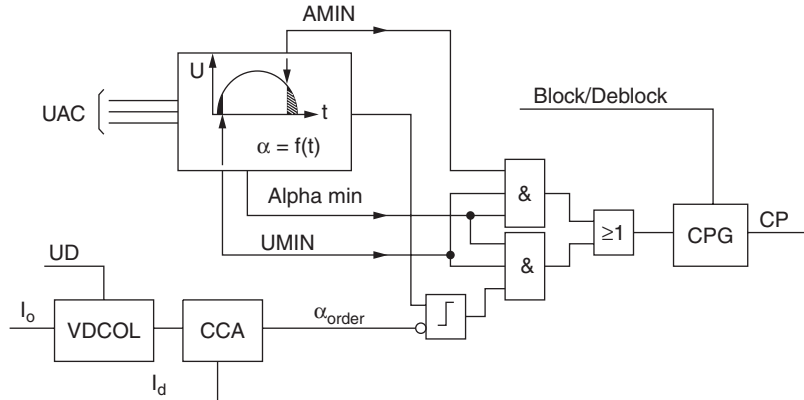


FIGURE 15-13 Converter firing control.

distribute them to the high-voltage valves, to minimize the reactive power consumption and achieve stable recoveries from large signal disturbances and faults in the ac network. Figure 15-13 shows these basic functions in the converter firing control (CFC).

The current order I_o is received from the pole power control. If the dc voltage is very low as during faults, the current order is limited by the voltage-dependent current order limiter, VDCOL. The alpha firing order is then limited as to its minimum and maximum value and minimum valve firing voltage (UMIN) in the converter firing control. Alpha min is used in inverter operation to prevent firing in rectifier operation. Minimum commutation margin control is used in inverter operation to maintain the minimum voltage time area to ensure successful recovery of forward blocking capability after valve conduction.

Figure 15-14 shows the static characteristics of the rectifier and inverter with addition of the VDCOL. The VDCOL acts to limit the dc current order below its normal set point if the dc current is above its break point and the dc voltage is lower than its break point. Taking into account dynamic performance, the current limitation is very fast acting during decreasing voltage due to faults, while the recovery is slower upon system voltage recovery depending on ac system strength or ability to deliver reactive power to the converter during recovery.

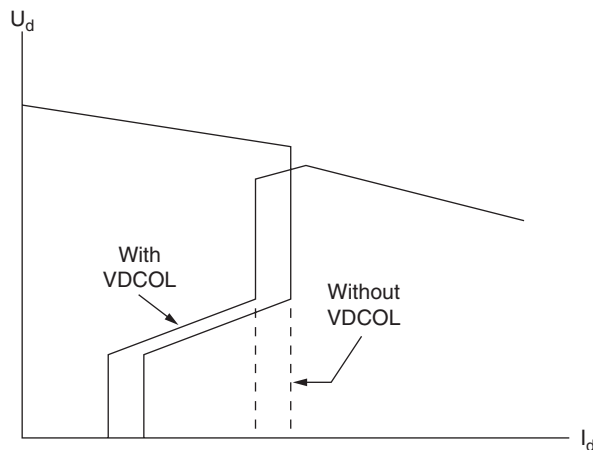


FIGURE 15-14 U_d - I_d characteristics with VDCOL.

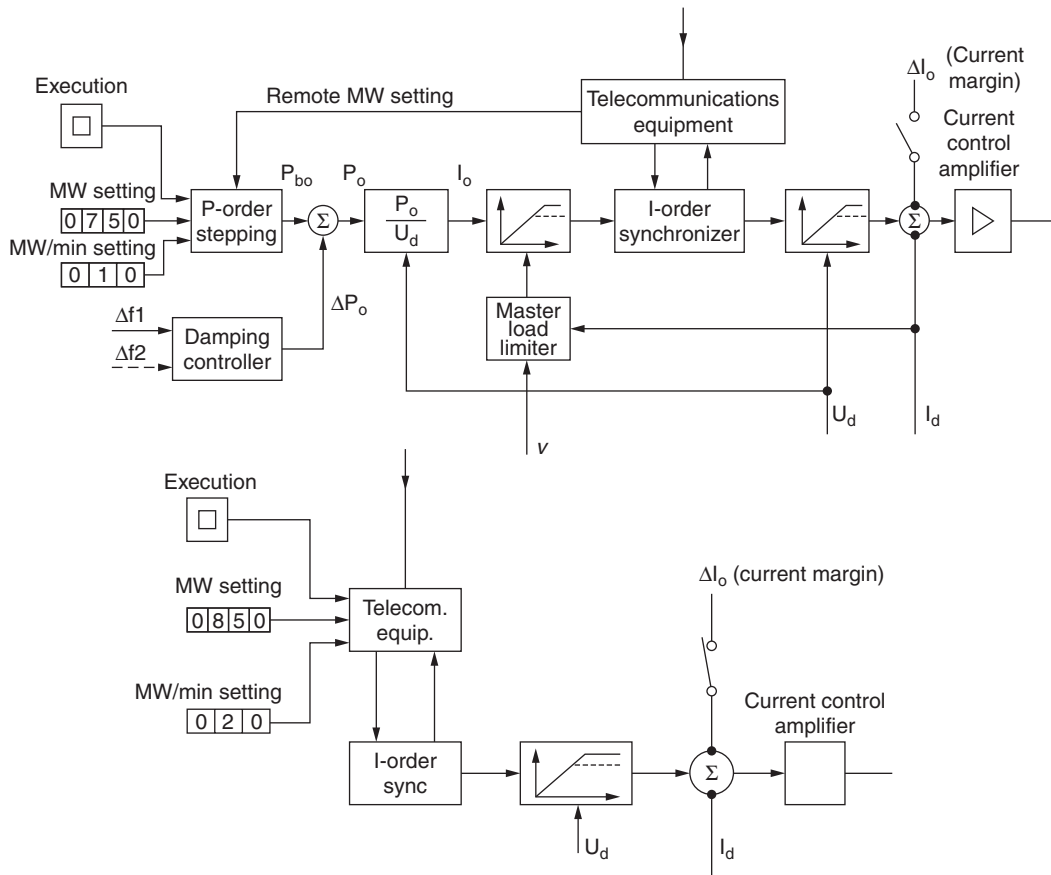


FIGURE 15-15 Master power control and current order synchronization.

The fundamental control functions described in the previous paragraphs are applied at the pole level and are independent of those on the other pole in a bipolar system. Coordination of the current orders between the terminals is required during ramping of the dc power during schedule changes. This is done during normal operation with secure communications between the terminals. Backup control strategies have been developed for communications outages. In a bipolar system, a master control is used for coordinated schedule changes and calculation of the current orders for each pole. The master control is used for compensation for loss of a pole by doubling the current order on the remaining pole subject to the equipment ratings. Figure 15-15 shows the current order coordination between the two terminals. For bipolar operation, the voltage fed to the power controller is the bipolar voltage assuring equal current orders to each pole. Upon loss of a pole this voltage is cut in half. Normally, the master control is intentionally slow being only used for schedule changes. For loss of a pole, however, its response time is fast. The master control can also handle supplemental control functions such as power oscillation damping and frequency control. Synchronization of the current order is such that the current margin is maintained.

15.3.5 Multiterminal Operation

The same control principles used for two-terminal operation can be applied to multiterminal operation with one terminal being assigned to voltage control, while the other terminals control their

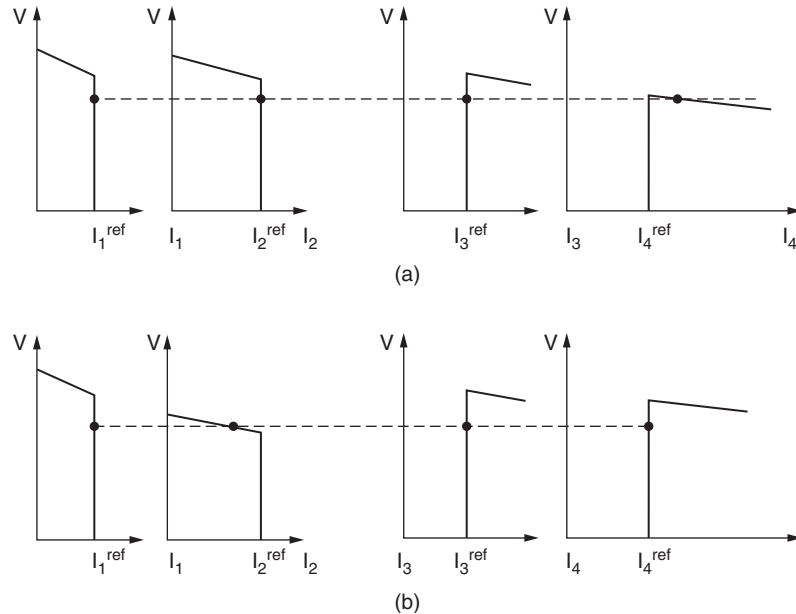


FIGURE 15-16 Static characteristics for 4-terminal HVDC system illustrating mode shift from inverter 4 (upper set) to Rectifier 2 (lower set) due to depressed ac voltage at Rectifier 2.

respective dc current orders (Fig. 15-16). The master control must also ensure that the sum of the rectifier current orders equals the sum of the inverter current orders on a per pole basis during all operating conditions. If one of the terminals is limited or tripped, the residual mismatch is allocated among the remaining stations according to prioritized distribution factors to ensure that Kirchhoff's law is met. If the tripped station is the voltage setting terminal (VST), one of the remaining stations must be assigned to voltage control. The same method for clearing dc line faults, force retard of the rectifier(s) to invert off the dc current, can be used along with fast-acting pole-isolating switches which in turn can be used to isolate a faulty terminal without using special purpose dc breakers.

15.3.6 Economics and Efficiency

The following factors influence the optimum solution for HVDC transmission systems:

- Power transfer requirements
- Transmission distance
- Capitalized cost of losses
- System configuration, that is, bipolar, monopolar, back-to-back OVHD line or cable system
- System connection voltages
- Relative system strength
- Reactive compensation requirements
- Environmental conditions
- Future expandability
- Transformer transport limitations

There is an economy of scale for HVDC transmission. It would cost less per kilowatt to transfer 3000 MW a distance of 800 km at ± 500 kV than it would to transfer 1000 MW. It would cost less

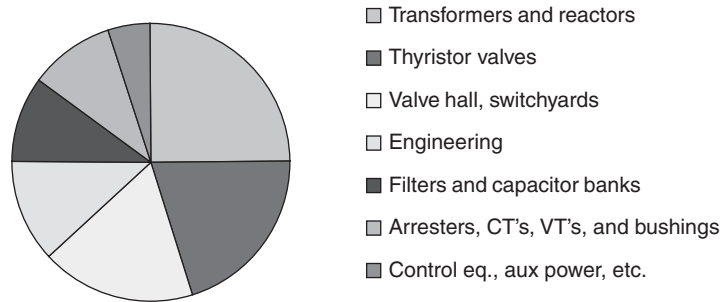


FIGURE 15-17 Terminal cost.

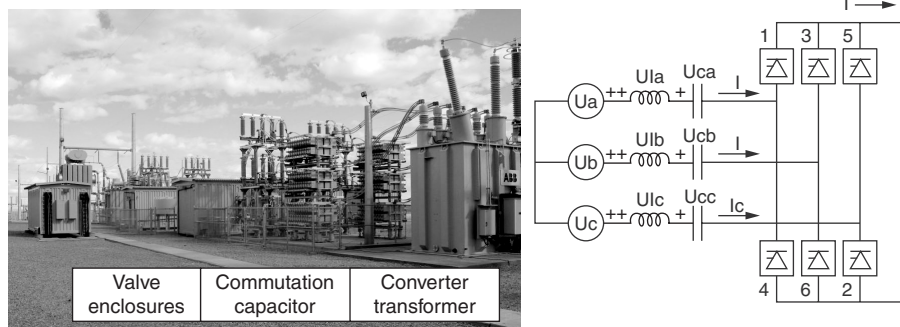
per kilowatt to transfer 600 MW over a monopolar submarine cable system than it would to transfer the same power on a 2-pole cable system with each pole rated at half the capacity. A 550-MW back-to-back asynchronous link would cost less per kilowatt than a 150-MW link.

HVDC applications at locations with relatively low short circuit capacities typically cost more per kilowatt due to constraints on reactive power compensation and dynamic overvoltage mitigation measures. A typical terminal cost breakdown of an HVDC transmission system for an OVHD line is shown in Fig. 15-17.

15.4 ALTERNATIVE CONFIGURATIONS

15.4.1 Capacitor-Commutated Converters

Converters with series capacitors connected between the valves and the transformers were introduced in the late 1990s for weak-system back-to-back applications. These converters are referred to as capacitor-commutated converters (CCC). The series capacitor provides some of the converter reactive power compensation requirements automatically with load current and provides part of the commutation voltage improving voltage stability. The overvoltage protection of the series capacitors is simple since the fault currents are limited by the impedance of the converter transformers. The CCC configuration allows higher power ratings in areas where the ac network is close to its voltage stability limit. The asynchronous Garabi interconnection between Brazil and Argentina consists of 4×550 MW parallel CCC links. The Rapid City Tie between the eastern and western interconnected systems consists of 2×100 MW parallel CCC links (Fig. 15-18). Both installations use a modular design with converter valves located within prefabricated electrical enclosures.

FIGURE 15-18 Rapid City Tie with modular 2×100 MW capacitor commutated converters.

15.4.2 Grid Power Flow Controller

A variation of the line-commutated design using a single 6-pulse converter has been used for a small back-to-back tie application. The term grid power flow controller (GPFC) has been used to describe this system design. By using a 6-pulse converter, there is no need for a second transformer secondary connection to obtain the requisite 30° phase displacement for 12-pulse operation. More ac harmonic filtering in the form of fifth and seventh branches is required, however. By using a 6-pulse converter and connecting the filters on the valve side, a simpler transformer connection can be utilized for matching the system voltage and blocking zero-sequence currents from flowing into the ac network. The ungrounded system has a large zero-sequence third order harmonic voltage component, however, appearing on the ungrounded neutrals and on the dc pole voltages, which increases the insulation levels. Despite using only one 6-pulse converter, the same number of series-connected thyristors is needed for the same dc voltage level.

15.4.3 Variable Frequency Transformer (VFT)

A technology that competes with HVDC for small capacity back-to-back ties in the 100 MW range was introduced in the early 2000s. A variable frequency transformer (VFT) is a machine rotating at the slip frequency between the two networks with high current between the rotor and stator passing through slip rings. The angle of the rotor is positioned to achieve a scheduled power flow by means of dc drives. The machine is connected to the network via step-up transformers. The reactive power demands of the VFT must be supplied by mechanically switched capacitor banks. Power control is slow due to having to move the inertia of the rotor, so it cannot respond quickly to a trip of generation on one the isolated network, for example. It cannot respond rapidly to variations in frequency or phase angle in the network so there will be inadvertent flow for fast variations. The VFT and its transformers provide an impedance, albeit a high one of around 40%, between the two networks. Therefore, the VFT will act as a voltage divider for faults in the network. This means that reactive power will be drained from one network due to a fault in the other. Losses of the VFT are higher than those for conventional HVDC.

15.5 STATION DESIGN AND EQUIPMENT

15.5.1 Thyristor Valves

For HVDC conversion, the thyristor valve must perform the following functions:

- Sequentially connect selected ac phases to the dc system per control pulses
- Conduct high current with low forward drop
- Block high voltages in both the forward and reverse directions
- Controllable and self monitoring
- Even voltage distribution and current turn-on
- Damp switching transients
- Fault tolerant and robust
- Accommodate cooling medium in high voltage environment

Thyristor valves are built up of series-connected thyristor modules and saturable reactors to limit valve turn-on di/dt. Each module contains a number of series-connected thyristors mounted on heat sinks. Each thyristor level is paralleled by an RC network for even voltage distribution and damping of commutation overshoots. Voltage measurement across each thyristor level is provided for thyristor monitoring, forward protection, and recovery protection.

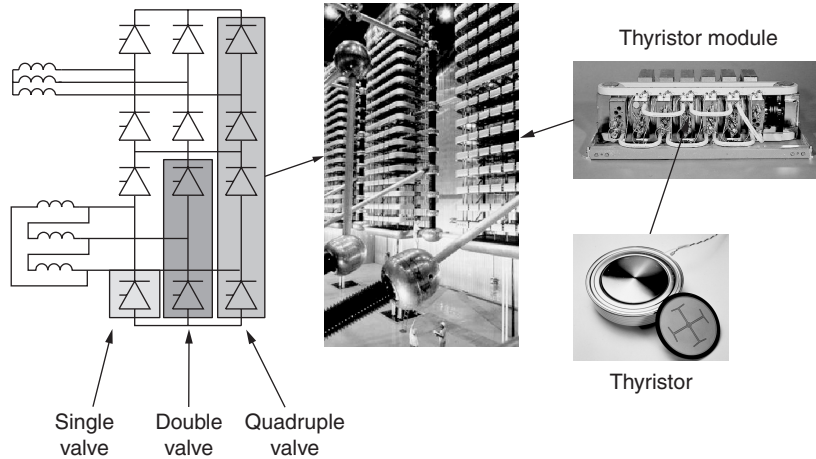


FIGURE 15-19 12-Pulse quadruple thyristor valve arrangement.

Each thyristor is coupled to the valve firing control at ground potential by means of two fiber optic links, one to carry valve trigger pulses to the thyristor gate circuit and the other for thyristor monitoring. Two types of thyristor triggering are used, electrically triggered thyristors (ETT) and light-triggered thyristors (LTT). Both triggering methods require voltage measurement at each thyristor level for monitoring and protection. ETT derives energy for gating from the RC damping circuit and gating is initiated by trigger pulses generated by light-emitting diodes. LTT thyristors have an optical turning-on region integrated on the thyristor wafer itself and use higher-power trigger pulses provided by laser diodes. Each thyristor level is equipped with forward protection which gates the thyristor on if the forward blocking voltage becomes too high due to, for example, absence of a trigger pulse. In inverter operation, during the thyristor recovery time after conduction, the forward protection level can be temporarily lowered. This is called recovery protection. ETT permits recovery protection to be implemented independently at the individual thyristor level (Fig. 15-19).

15.5.2 Converter Transformers

Converter transformers are the link between the ac and dc systems. They provide isolation between the two systems, preventing dc voltage and current from reaching the ac system. They also provide the phase displacement necessary for 12-pulse operation through wye- and delta-valve winding connections. Converter transformers have regulating windings with load-tap changers to maintain the ac voltage and converter firing angle within a narrow band across the entire converter operating range. Converter transformer impedance also limits the valve short-circuit levels to within their handling capability. As shown by Eq. 15-12, the 3-phase rating of the converter transformer for a 6-pulse bridge is proportional to U_{diON} and I_{dN} .

Converter transformer losses are those due to the fundamental frequency of load current plus those due to harmonics. The insulation design for converter transformers must take into account the direct voltage stresses superimposed on the normal ac voltage stresses. The ac stresses distribute as it would in a capacitive network while the dc voltage stresses distribute as according to a resistive network.

Transformer design depends on the bridge rating and type of converter connection and takes into account spare parts requirements and transport restrictions. For a small back-to-back, for example, a

3-phase bank with double secondary (wye and delta) may be used, that is, nine windings on a single core structure in a common tank for each 12-pulse converter bridge. For larger converters, three, single-phase transformers with double secondary windings may be used for each 12-pulse bridge. For the largest converter ratings where there may be some transport limitations, single-phase, two-winding transformers may be used, that is, six transformers per 12-pulse bridge (Fig. 15-20).

15.5.3 Smoothing Reactor

A smoothing reactor is connected in series with the converter on the dc side to reduce the harmonic ripple in the dc current as well as reduce transient currents during faults. The smoothing reactor also protects the converter valves from voltage surges coming in on the dc line. The dc smoothing reactor together with shunt-connected dc filters serve to limit telephone interference disturbing currents from flowing on the dc line. Most smoothing reactors are air-core, naturally air-cooled.



FIGURE 15-20 Single-phase, three-winding converter transformer for a 3100 MW bipole.

15.5.4 AC Filters

Converters inject harmonic currents into the ac network. AC filters are used to prevent these harmonic currents from flowing into the ac network impedance causing voltage distortion and induced telephone interference in the audible frequency range. AC filters provide a low-impedance path to ground at the harmonic frequencies. The ac filter comprises high-voltage capacitor banks and lower-voltage reactors, resistors, and capacitors, which together form a circuit tuned to the characteristic harmonic(s). The lower-order filters are single- or double-tuned, band-pass filters, while the higher harmonics are often taken care of by high-pass filters (Fig. 15-21).

AC harmonic filter design involves calculating the harmonic currents generated and estimating harmonic impedance characteristics of the ac network across the whole range of operating conditions and tolerances. A filter design is then developed to meet the required performance requirements. Filter components are then rated with an adequate margin the particular application.

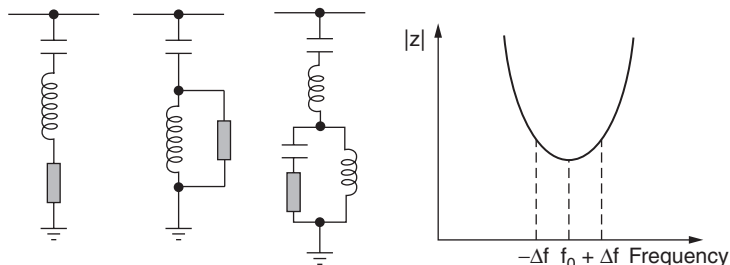


FIGURE 15-21 (a) Bandpass filter, (b) highpass filter, (c) double bandpass filter, (d) impedance vs. frequency.

The most common filter performance criteria are individual and total harmonic voltage distortion, D_T and D_h , and weighted telephone interference factor (TIF), calculated as follows:

$$D_h = 100 \times V_h/V_1$$

$$D_T = \left(\sum_{h=2}^{49} D_h^2 \right)^{1/2}$$

$$\text{TIF} = \left[\sum_{h=2}^{49} \left(F_h \cdot \frac{V_h}{V_1} \right)^2 \right]^{1/2}$$

15.5.5 DC Filters

Filters are required on the dc side for dc to limit interference with communication circuits, which are inductively coupled to the dc line, for example, parallel telephone lines. The design criterion for dc harmonic filters is a function of relating to the flow of harmonic currents at any point along the dc line to the interference with adjacent telephone lines. Significant parameters are the relative location of telephone lines with respect to the dc line, their shielding, the presence of any ground wires, and the earth's resistivity. This criterion is typically expressed as equivalent disturbing current I_{eq} . Disturbance levels are lower in normal balanced bipolar mode, due to cancellation effects, than in monopolar mode.

DC filter design must take into account the entire dc network with all harmonic sources and operating modes. DC harmonic filters consist of band-pass and high-pass filters connected in shut outside the smoothing reactor. Many modern HVDC links use a single 12th harmonic band-pass filter on each pole with active filtering for the higher order harmonics (Fig. 15-22). Active filtering consists of measuring the actual dc-side harmonics from the converter and counter-injecting the same amount with opposite polarity.

15.5.6 Power Line Carrier (PLC) Filters

Commutation in HVDC converters discharges stray capacitances and generates electrical noise at the lower end of the power line carrier spectrum (PLC), that is, strongest at 30 to 70 kHz. This noise may pass onto the interconnecting ac and dc lines. Where low-level carriers exist at the lower end of the PLC spectrum, filters may be required.

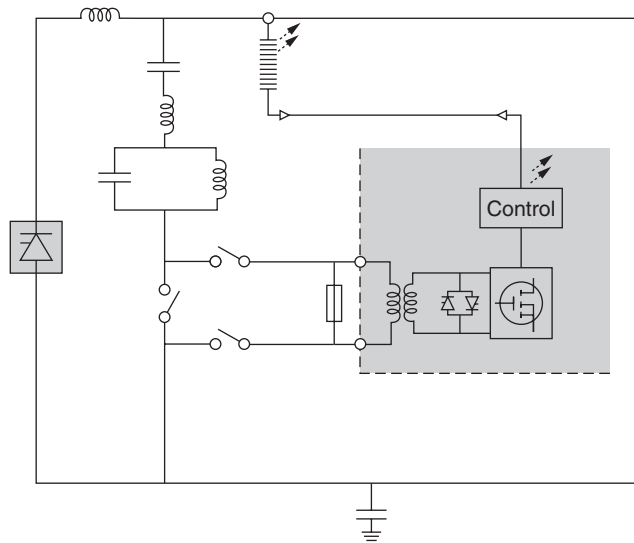


FIGURE 15-22 Active dc harmonic filter.

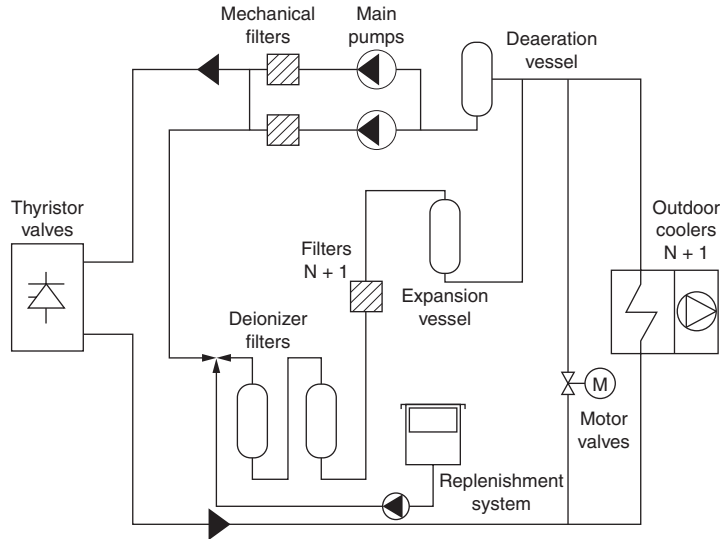


FIGURE 15-23 Closed-loop water cooling system.

15.5.7 Valve Cooling System

Thyristor valves must be cooled to avoid too high thyristor junction temperatures and to dissipate heat from the valve damping circuits and reactors. Valve cooling is accomplished by a deionized water loop circulating via insulated tubing to the individual thyristor heat sinks. Waste heat is passed to outdoor liquid-to-air coolers. Redundant variable speed pumps and coolers fed from redundant power supplies are used for reliability, availability, and ease of maintenance (Fig. 15-23).

15.5.8 Reliability and Availability

To meet high levels of reliability and availability plus facilitate ease of maintenance, redundancy is commonly used in HVDC converter station design. Typical guaranteed unavailability values are 0.5% for forced outages and 1.0% for scheduled outages.

Redundant series-connected thyristor levels are used in the valves. The failure mode is short circuit of the thyristor, so operation can continue until a convenient time for restoring full redundancy. Redundant cooling pumps and cooler units are used. Use of redundant control and protection systems is often used. For major main circuit components, spare parts are provided at site to minimize the time for replacement.

15.6 VOLTAGE SOURCE CONVERTER (VSC) BASED HVDC TRANSMISSION

15.6.1 System Characteristics

Conventional HVDC transmission employs line-commutated, current-source converters with thyristor valves. These converters require a relatively strong synchronous voltage source in order to commute. The conversion process demands reactive power from filters, shunt banks, or series capacitors, which are an integral part of the converter station. Any surplus or deficit in reactive power must be

TABLE 15-2 HVDC VSC Projects Listing

Project	Year commissioned	Power rating, MW	DC voltage, kV	Cable, km	Location
Hellsjon	1997	3	± 10	10	Sweden
Gotland Light	1999	50	± 80	70	Sweden
Direct Link	2000	3×60	± 80	65	Australia
Tjaerborg	2000	7.2	± 9	4.4	Denmark
Cross Sound Cable	2002	330	± 150	40	United States
Murraylink	2002	200	± 150	180	Australia
Troll Offshore	2005	2×42	± 60	70	Norway
Estlink	2006	350	± 150	105	Estonia/Finland

accommodated by the ac system. This difference in reactive power needs to be kept within a given band to keep the ac voltage within the desired tolerance. The weaker the system or the further away from generation, the tighter the reactive power exchange must be to stay within the desired voltage tolerance.

HVDC transmission using voltage-source converters (VSC) with pulse-width modulation (PWM) was introduced as HVDC Light[®] in the late 1990s by ABB. These VSC-based systems are force-commutated with insulated-gate bipolar transistor (IGBT) valves and solid-dielectric, extruded HVDC cables (Table 15-2).

HVDC transmission and reactive power compensation with VSC technology has certain attributes which can be beneficial to overall system performance. VSC converter technology can rapidly control both active and reactive power independently of one another. Reactive power can also be controlled at each terminal independent of the dc transmission voltage level. This control capability gives total flexibility to place converters anywhere in the ac network since there is no restriction on minimum network short-circuit capacity. Forced commutation with VSC even permits black start, that is, the converter can be used to synthesize a balanced set of 3-phase voltages like a virtual synchronous generator. The dynamic support of the ac voltage at each converter terminal improves the voltage stability and increases the transfer capability of the sending and receiving end ac systems.

15.6.2 Applications

The aforementioned attributes of VSC-based HVDC transmission makes it especially suitable in certain applications. These applications are summarized as follows:

Underground Cable. HVDC cable systems do not face the distance limitations or suffer the higher losses of ac cable systems. Therefore, long-distance HVDC cable transmission is possible. Extruded HVDC cables are lighter, more flexible, and easier to splice than the mass-impregnated, oil-paper cables (MIND) used for conventional HVDC transmission, thus making them more conducive for land cable applications where transport limitations can drive up costs. The lower cost cable installations made possible by the extruded HVDC cables makes long-distance underground transmission economically feasible for use in areas with ROW constraints.

Power Supply to Insular Load. Forced-commutation, dynamic voltage control, and black-start capability allow VSC HVDC transmission to serve isolated loads on islands over long-distance submarine cables without any need for running expensive local generation.

Offshore. The VSC transmission is compact and can feed production or transportation loads on offshore oil or gas platforms from shore. This can eliminate the need for more expensive, less efficient, or higher emission offshore power production. The VSC converters can operate at variable frequency to more efficiently drive large compressor or pumping loads using high-voltage motors.

Asynchronous Interconnections. Interconnections between asynchronous networks are often at their periphery where the networks tend to be weak relative to the desired power transfer. The dynamic voltage support and improved voltage stability offered by VSC-based converters permits higher power transfers without as much need for ac system reinforcement. The VSC converters do not suffer commutation failures allowing fast recoveries from nearby ac faults. Economic power schedules, which reverse power direction, can be made without any restrictions since there is no minimum power or current restrictions.

Urban Infeed. Power supply for large cities depends on local generation and power import capability. Local generation is often older and less efficient than newer units located remotely. Often, however, the older, less-efficient units located near the city center must be dispatched out-of-merit because they must be run for reliable voltage support or inadequate transmission. New transmission into large cities is difficult to site due to ROW and land-use constraints. Compact VSC-based underground transmission circuits can be placed on existing dual-use ROW to bring in power as well as provide voltage support, allowing a more economical power supply without compromising reliability. The receiving terminal acts like a virtual generator delivering power and voltage regulation. Stations are compact and housed mainly indoors making siting in urban areas somewhat easier.

Outlet Transmission for Large-Scale Wind Generation. Large remote wind generation arrays require a collector system, reactive power support, and outlet transmission. Transmission for wind generation must often traverse scenic or environmentally sensitive areas or bodies of water. The VSC-based HVDC transmission allows efficient use of long-distance land or submarine cables and provides reactive support to the wind generation complex.

Multiterminal Systems. The VSC HVDC transmission reverses power through reversal of current direction rather than polarity. This makes it easier to reverse power at an intermediate tap independently of the main power flow direction since voltage polarity reversal is not required. Conventional HVDC transmission requires switching for converter opposite pole connection or polarity reversal.

15.6.3 VSC Station Configuration and Design

HVDC transmission systems based on VSC converter technology are configured as shown in Fig. 15-24.

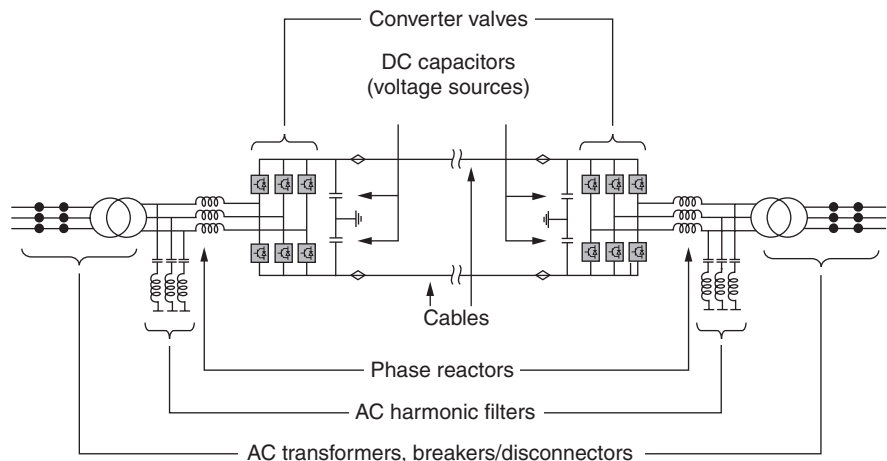


FIGURE 15-24 VSC-based HVDC.

The transmission circuit consists of a bipolar two-wire HVDC system with converters connected pole-to-pole. The dc capacitors are used to provide a dc voltage source. The dc capacitors are grounded at their electrical center point to establish the earth reference potential for the transmission system. There is no earth return operation. The converters are coupled to the ac system through ac phase reactors and power transformers. Harmonic filters are located between the phase reactors and power transformers. Therefore, the transformers are exposed to no dc voltage stresses or harmonics loading allowing use of ordinary power transformers.

A simplified single line diagram for a two-level VSC converter station is shown in Fig. 15-25. Principal station components are described in the following paragraphs.

Power Transformer. The transformer is an ordinary single- or 3-phase power transformer with load tap changer. The secondary voltage, that is, the filter bus voltage, can be controlled with the tap changer to achieve the maximum active and reactive power, both consumption and generation, from the converter. The tap changer is located on the secondary side, which has the largest voltage swing, and also to ensure that the ratio between the line winding and a possible tertiary winding is fixed. The current in the transformer windings contains hardly any harmonics and is not exposed to any dc voltage. In order to maximize the active power transfer, the converter can generate a low frequency zero-sequence voltage (<0.2 pu), which is blocked by the ungrounded transformer secondary winding.

The transformer may be provided with a tertiary winding to feed the station auxiliary power system.

Converter Reactors. The converter reactor is installed in series in each phase and is one of the key components in a voltage source converter to permit continuous and independent control of active and reactive power.

The main purposes of the converter reactors are to:

- Provide low-pass filtering of the PWM pattern to give the desired fundamental frequency voltage. The converter generates harmonics related to the switching frequency. The harmonic currents are blocked by the converter reactor and the harmonic content on the ac bus voltage is reduced by an ac filter.
- Provide active and reactive power control. The fundamental frequency voltage across the reactor defines the power flow (both active and reactive) between the ac and dc sides. Refer to typical P-Q diagram and active and reactive power definitions.
- Limit the short-circuit currents.

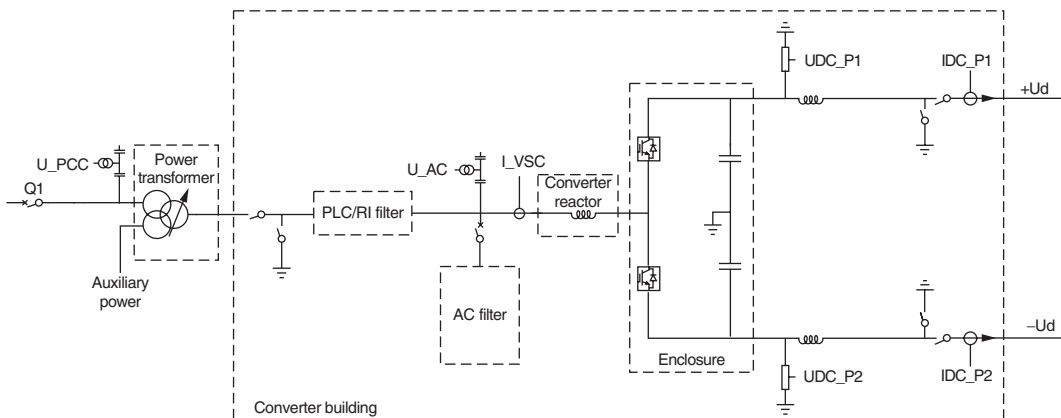


FIGURE 15-25 Simplified SLD for VSC station.

DC-Capacitors. The primary objective of the valve dc side capacitor is to provide a low-inductance path for the turn-off switching currents and provide energy storage. The capacitor also reduces the harmonic ripple on the direct voltage. Disturbances in the system (e.g., ac faults) will cause dc voltage variations. The ability to limit these voltage variations depends on the size of the dc side capacitor. Since the dc capacitors are used indoors, dry capacitors are used.

AC-Filters. Voltage source converters can be operated with different control schemes most of which use pulse width modulation to control the ratio between dc and ac side fundamental frequency voltage. Looking at the ac voltages on the converter side of the reactor, the voltage to ground consists of a square wave as indicated by Fig. 15-3. Connection of a large voltage source converter to a transmission or distribution system requires ac filters to remove the high-frequency components from introducing distortion or interference into the network. This is achieved by means of the converter reactor and the ac filters. The harmonics generated by VSC converters with PWM are higher in frequency than those from conventional HVDC converters. Therefore, smaller filter components can be used to meet performance requirements without large fundamental frequency reactive power generation. This makes the VSC converters better suited to weak-system applications.

The distorted waveform of the converter terminal voltage can be described as a series of harmonic voltages

$$E = \sum_{h=1} E_h \cos(h\Omega_1 t + \alpha_h)$$

where E_h is the h th harmonic EMF. The magnitude of the harmonic EMFs will, naturally, vary with the dc voltage, the switching frequency (or pulse number) of the converter, etc. It will also depend on the chosen PWM control method and topology of the converter. For example, a converter can use sinusoidal PWM with third harmonic injection, that is, when a third harmonic is added on the fundamental frequency modulator to increase the power rating of the converter, or some form of harmonic cancellation such as optimized pulse width modulation, OPWM, can be used. Higher level converters can also be used to switch between a higher number of dc voltage levels, for example, a three level converter can switch between the positive, zero, and negative dc voltage level. In a typical VSC scheme, ac filters contain two- or three-tuned or high-pass filter branches, which can be either grounded or ungrounded.

DC Filters. For VSC converters in combination with extruded dc cables, the filtering on the dc side by the converter dc capacitor and the line smoothing reactor on the dc side is considered to give sufficient suppression of harmonics. However, under certain circumstances, if the dc cable route shares the same right of way or runs close by telephone circuits, railroad signaling wires, or similar, there is a possibility of exposure to harmonic interference from the cable. Under these circumstances and for conditions where a local preventive measure is not feasible, for example, improving the shielding of subscriber wires, the communications company should be consulted for permissible interference limits. A typical requirement can be expressed as an equivalent weighted residual current fed into the cable pair at each station. The current is calculated as

$$I_{eq} = (1/P_{800}) \times \sqrt{\sum_h (P_{hf_1} \times I_h)^2}$$

where I_{eq} = weighted, 800 Hz equivalent disturbing current

I_h = vector sum of harmonic currents in cable pair conductors and screens at harmonic h

P_{hf_1} = weighting at the frequency of h times the fundamental frequency

High-Frequency (HF) Filters. In voltage source converters, the necessarily high dv/dt in the switching of valves means that the high-frequency (HF) noise generation is significantly higher than for conventional HVDC converters. To prevent this HF noise spreading from the converter to the connected power grids, particular attention is given to the design of the valves, to the shielding of the housings, and to ensuring proper HF grounding connections.

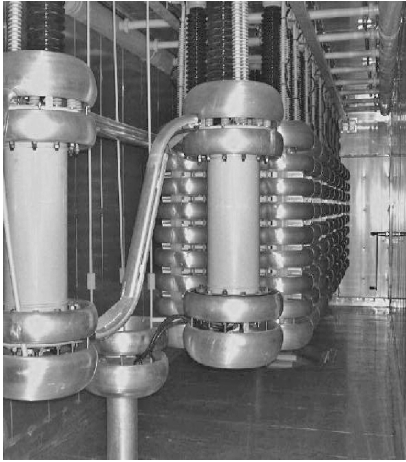


FIGURE 15-26 IGBT valve stacks with corona shields.

IGBT Valves. The insulated gate bipolar transistor (IGBT) valves used in VSC converters are comprised of series-connected IGBT positions. The IGBT is a hybrid device exhibiting the low forward drop of a bipolar transistor as a conducting device (Fig. 15-26). Instead of the regular current-controlled base, the IGBT has a voltage-controlled capacitive gate, as in the MOSFET device.

A complete IGBT position consists of an IGBT, an antiparallel diode, a gate unit, a voltage divider, and a water-cooled heat sink. Each gate unit includes gate-driving circuits, surveillance circuits, and optical interface. The gate-driving electronics control the gate voltage and current at turn-on and turn-off, to achieve optimal turn-on and turn-off processes of the IGBT.

To be able to switch voltages higher than the rated voltage of one IGBT, many positions are connected in series in each valve similar to thyristors in conventional HVDC valves. All IGBTs must turn on and off at exactly the same moment,

to achieve an evenly distributed voltage across the valve. Higher currents are handled by paralleling IGBT components or press packs.

15.6.4 Converter Control

The fundamental frequency base apparent power of the converter measured at the filter bus between phase reactor and the ac harmonic filters along with its active and reactive power components are defined by the following equations. Voltage and current phasors used in these equations are according to Fig. 15-27.

$$S_b = P + jQ = \sqrt{3} \times U_F \times I_R^*$$

$$P = \frac{U_F \times U_C \times \sin \delta}{\omega L}$$

$$Q = \frac{U_F \times (U_F - U_C \times \cos \delta)}{\omega L}$$

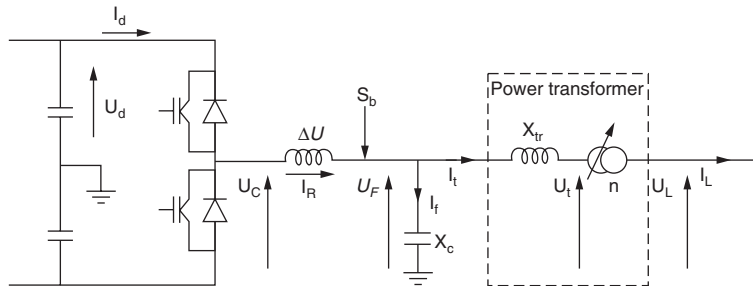


FIGURE 15-27 Voltage source converter.

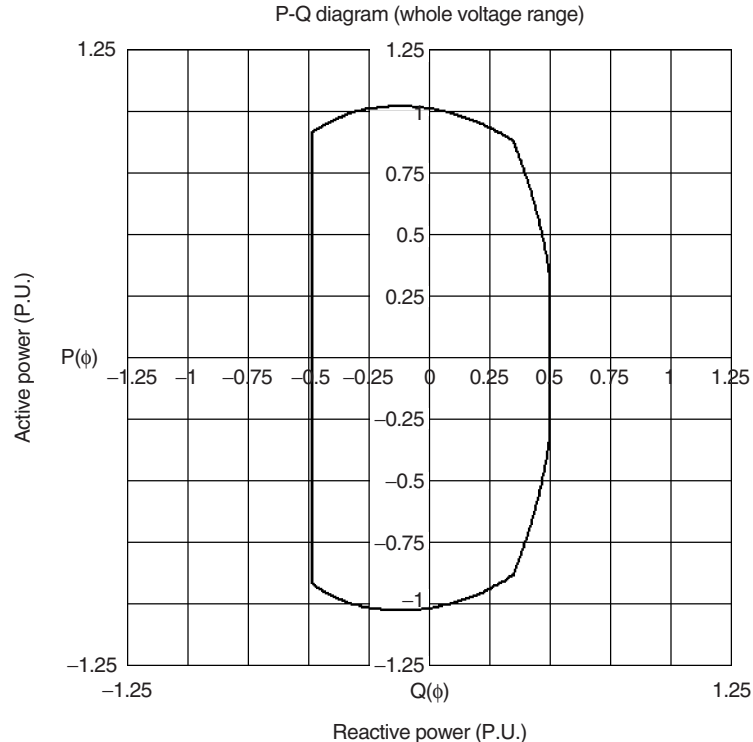


FIGURE 15-28 VSC station net P-Q characteristics with practical limitations.

The inductance of the converter phase reactor is represented by L , and the phase angle between the filter voltage U_F and converter voltage U_C is represented by δ .

The equations illustrate that the power can be controlled by changing the phase angle of the converter voltage with respect to the filter bus voltage, whereas the reactive power can be controlled by changing the magnitude of the converter voltage with respect to the filter bus voltage. By controlling these two aspects of the converter voltage operation in all four quadrants is possible as illustrated in the converter P-Q characteristics shown in Fig. 15-28. This means that the converter can be operated in the middle of its reactive power range near unity power factor to maintain dynamic reactive power reserve for contingency voltage support. It also means that the power transfer can be changed rapidly without altering the reactive power exchange with the ac network or waiting for switching of shunt compensation.

Being able to independently control ac voltage magnitude and phase relative to the system voltage allows use of separate active and reactive power control loops for HVDC system regulation.

The active power control loop can be set to control either the active power or the dc side voltage. In a dc link, one station will then be selected to control the active power while the other must be set to control the dc side voltage. The reactive power control loop can be set to control either the reactive power or the ac side voltage. Either of these two modes can be selected independently at either end of the dc link (Fig. 15-29).

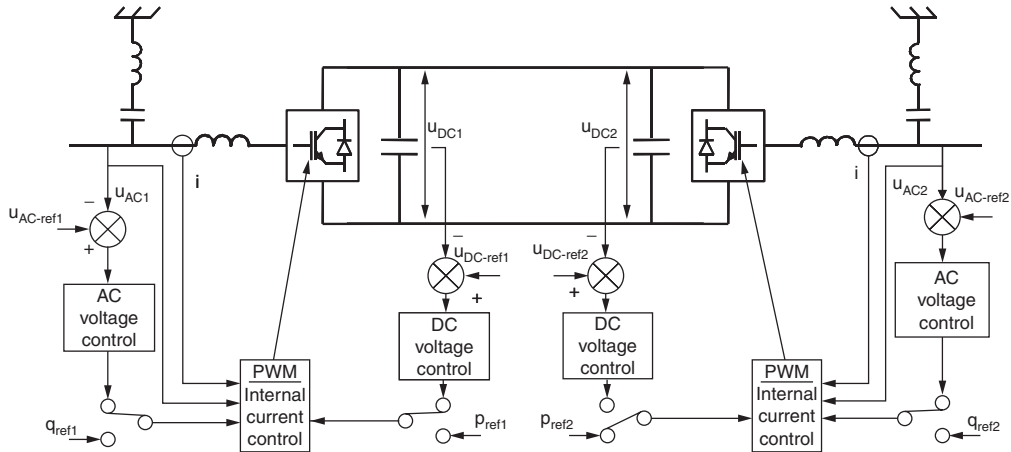


FIGURE 15-29 VSC-based HVDC system control.

15.6.5 Pulse-Width Modulation (PWM) and Harmonic Generation

Pulse width modulation (PWM) of voltage source converters enables independent control of active and reactive power at a constant HVDC voltage using simple two-level converter topology as shown in Fig. 15-30.

A two-level VSC converter can synthesize a balanced set of 3-phase ac converter voltages by injecting either the positive or negative dc voltage on the converter side of the phase reactor. By varying the duration of the positive or negative voltage injections, a sinusoidal voltage with fundamental component at the system frequency can be created. Various PWM switching patterns can be used to minimize harmonics and lower converter switching losses. A PWM pattern with harmonic cancellation or optimized PWM and its harmonic content is shown in Fig. 15-31.

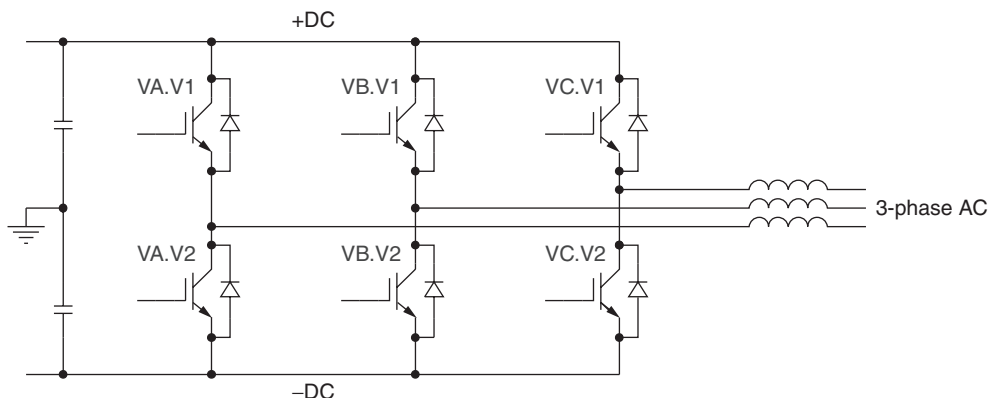


FIGURE 15-30 VSC two-level converter topology.

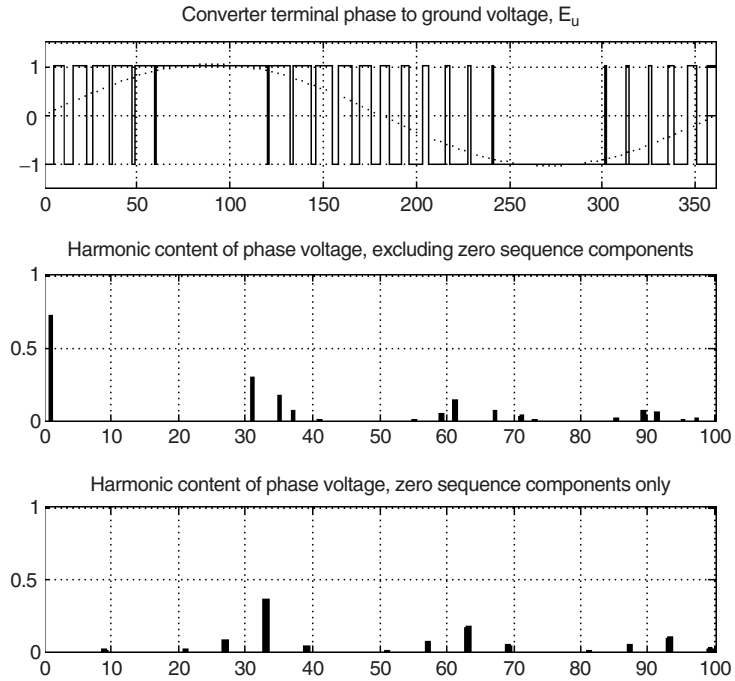


FIGURE 15-31 PWM with harmonic cancellation for two-level VSC.

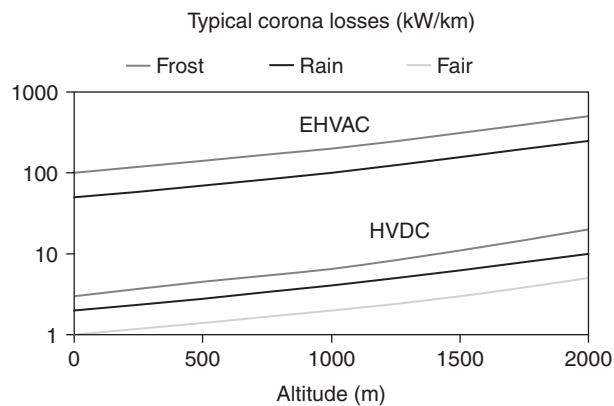


FIGURE 15-32 Foul weather corona loss comparison of EHVAC and HVDC Lines as a function of altitude.

15.7 OVERHEAD LINES AND CABLES

15.7.1 Overhead Transmission Lines

General design criteria for transmission lines can be grouped in the following five categories:

- Power transmission capability
- Power losses
- Insulation coordination
- Corona and field effects
- Mechanical loading

Power transmission capacity is limited by the conductor sag and thermal capacity of the line for the ambient conditions. Emergency loading limits are sometimes used taking into account local conditions and increased sag. These factors affect both EHV ac and HVDC lines. Permissible power transfer levels on EHV ac lines are also affected by surge impedance loading, reactive power compensation, voltage profile, contingency reserve, and stability limits. Transmission on HVDC lines is not limited to reactive power constraints. The HVDC lines cannot become overloaded since the power flow is controlled, therefore contingency reserve is not usually required.

Power losses are due to resistive losses and corona losses. For a given ampacity, resistive losses are lower for an HVDC line than an EHV ac line since the same current is flowing in two sets of conductors in a bipolar dc line compared to three conductors for a 3-phase ac line. Furthermore, the ac resistance is somewhat higher due to skin effect. Although corona losses for EHV ac lines are about the same as those for HVDC lines during fair weather conditions, they increase much more during foul weather conditions, for example, rain, frost, or snow (Fig. 15-32). This means that larger conductor bundles are needed for EHV ac. Dimensions of corona rings are less critical with HVDC. Due to the lower corona levels with HVDC lines, especially during foul weather, fewer bundled conductors are required to meet given requirements on audible noise (AN) or radio interference (RI).

Air clearance requirements are significantly lower for HVDC lines than for EHV ac lines but are more sensitive to altitude effects. Switching surges are significantly lower for HVDC lines than for EHV ac lines. Switching overvoltages govern the clearances for EHV ac lines whereas lightning overvoltages govern the clearances for HVDC lines.

Insulators made of conventional or composite materials can be used for HVDC. The dc operating voltage grading across the insulator string is resistive rather than capacitive. The lower clearance requirements on insulator string length together with the resistive voltage grading make insulator creepage distance more important for HVDC insulators, especially in areas prone to atmospheric pollution. The frequency and intensity of rain are also an important factor since rain washes away accumulated deposits periodically more so on the top surfaces. Additional insulator creepage distance can be achieved with larger sheds, longer skirts, or longer string lengths. A creepage distance of 2.8 cm/kV for lightly contaminated areas can be considered typical. Special considerations exist for insulator cap-an-pin design and choice of materials due to potential for external leakage currents. Collector rings can be used to trap contaminants mitigating uneven deposition along the insulator surface in polluted areas.

There is no electromagnetic induction from HVDC lines. There is an essential difference in acceptance level for dc fields than for ac fields with higher levels for static fields. The International Commission on Nonionizing Radiation Protection (ICNIRP), places a guideline of 40 μT on the maximum static electromagnetic field for continuous exposure to the general public. This compares to the nominal earth magnetic field of 50 μT . The dc magnetic field is very small for two conductors with current flowing in opposite directions at distances several multiples of the conductor spacing.

The HVDC line towers must bear less static and dynamic loading than EHV ac towers due to fewer conductors and insulators. The ROW requirements are narrower with HVDC. In areas where ROW widths are constrained, vertical configurations require less tower height. Balanced structure loading for vertical configurations can be achieved by use of “portal” structures with pole conductors passing through the center of the structure suspended with V-strings.

15.7.2 Underground and Submarine Cables

The HVDC is attractive for higher power transfers over longer distances due to the absence of charging currents and reactive power losses. Fewer cables are needed than for a 3-phase ac circuit. Furthermore, since there is no induction effect with HVDC, cable sheaths do not need to carry the same currents and steel armor can be used for stronger submarine cables.

In ac cables, stress created by the electrical field is distributed in inverse proportion to the capacitance of the cable dielectric. This results in the highest stresses close to the conductor. In dc cables, voltage distribution is determined by insulation resistance and space charges and is dependent on temperature. At higher conductor to sheath temperature gradient, the stress may become highest near the sheath.

Two types of cables are in common use for HVDC transmission, mass-impregnated, nondraining paper-insulated solid cables (MIND), and extruded polymer cables for lower voltage VSC applications (Figs. 15-33 and 15-34). Fig. 15-35 shows voltage waveforms for transformer secondary winding, thyristor valve and dc voltage inside the smoothing reactor. With conventional HVDC, power reversal is achieved by voltage polarity reversal of the cable and 12-pulse harmonic voltages can be imposed on the cable insulation depending on the dc filter design. Fig. 15-36 shows phase reactor voltage, valve voltage and direct voltage for a VSC converter. With VSC transmission, the voltage polarity is constant regardless of transmission direction and switching transients are absorbed by the dc capacitor.

15.7.3 Ground Electrodes

Ground and sea return operation has been used for HVDC transmission to decrease investment costs and lower losses in monopolar submarine cable systems and as a temporary return path for pole outages in bipolar systems. Electrode design always ensures safe step potentials, but other important design factors must be taken into account.

Continuous earth return operation is not always possible due to local soil and geological conditions. With typical earth characteristics, return current penetrates deep within the earth and earth surface potential gradients are low and fall off



FIGURE 15-33 MIND cables for deep sea applications with conventional HVDC.

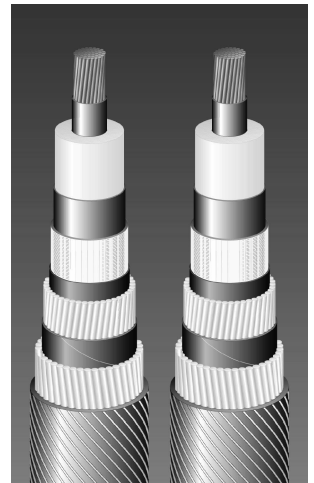


FIGURE 15-34 Extruded polymer cables for deep sea applications with VSC-based HVDC.

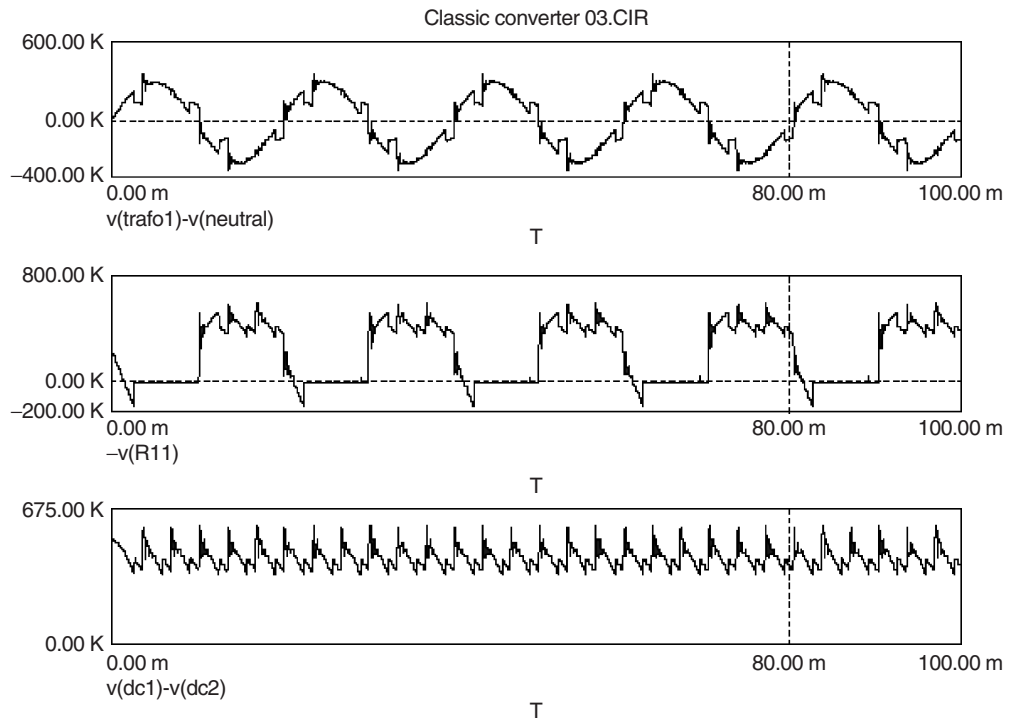


FIGURE 15-35 Voltages for conventional HVDC transmission. Top trace—converter transformer voltage; Middle trace—valve voltage; Bottom trace—direct voltage (inside smoothing reactor).

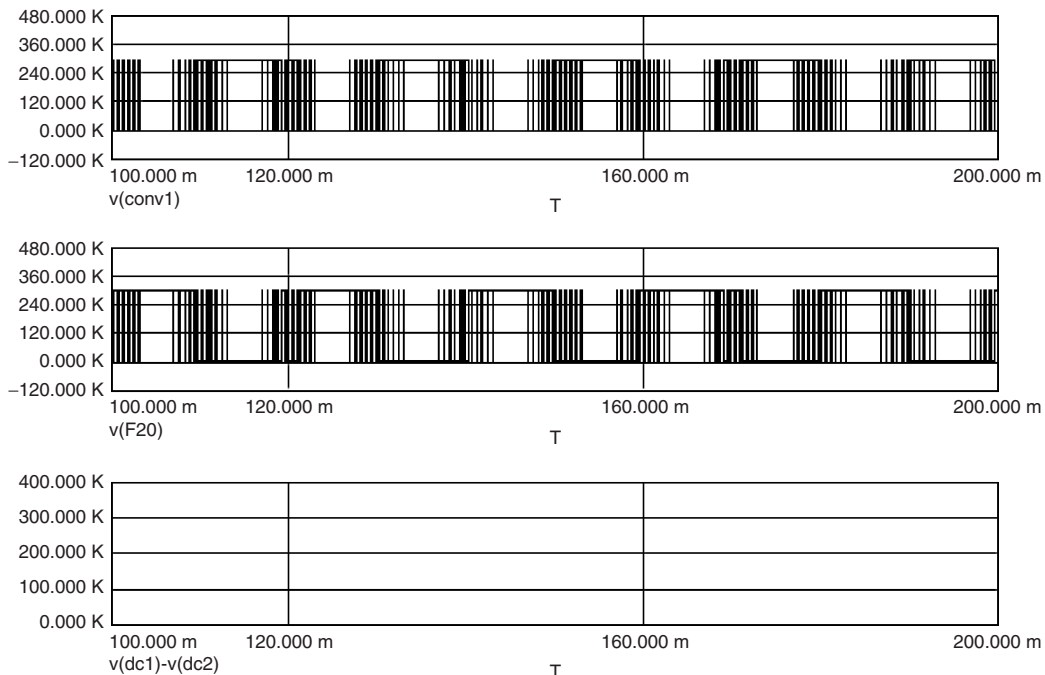


FIGURE 15-36 Voltages for VSC-based HVDC transmission. Top trace—phase reactor voltage; Middle trace—valve voltage; Bottom trace—direct voltage.

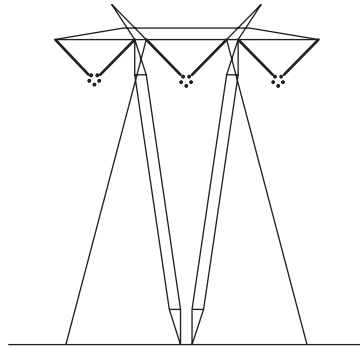


FIGURE 15-37 UHVAC line design.

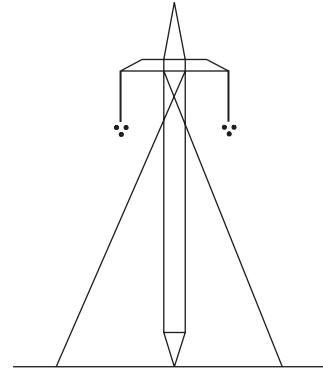


FIGURE 15-38 UHVDC line design.

rapidly with distance from the electrode. In cases with shallow, high-resistivity underlying bedrock, however, the current tends to flow more in the surface layer and the potential gradient extends further from the electrode site. If other conducting underground utilities, such as pipelines, traverse the potential gradient near the electrode, there is risk of stray current pickup and discharge. Over a long period of time, stray current discharge could cause localized corrosion. Corrosion mitigation

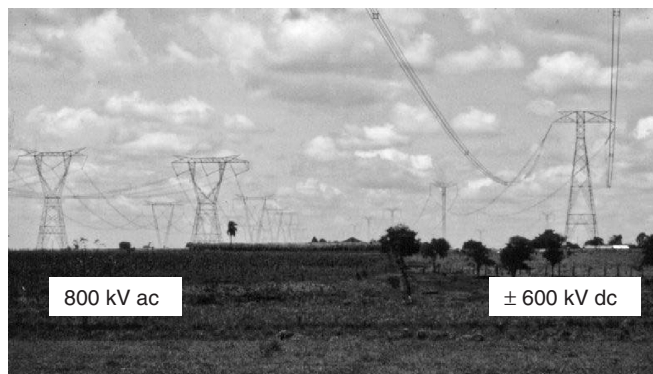
FIGURE 15-39 800 kV EHV ac and ± 600 kV dc.

TABLE 15-3 Comparison of Number of Lines for Given Power Transfer with UHVAC and UHVDC

	kv	Cond. diam.	Thermal limit (line)	Thermal limit(s/s)	SIL	1.5 × SIL	Required no. of lines	
		mm	GW	GW	GW	GW	8 GW	12 GW
EHVAC	800	5 × 35	7.5	5.5	2.5	3.8	4	5
	1000	8 × 35	15.0	6.9	4.3	6.5	3	3
HVDC	±600	3 × 50	8.0	5.8	n.a.	n.a.	2	3
	±800	5 × 50	17.7	5.8	n.a.	n.a.	2	3

methods, such as controlled cathodic protection systems, insulating flanges, or sacrificial anodes, can be used or the ampere-hours for earth return operation can be limited through use of metallic return.

15.8 ULTRA-HIGH VOLTAGE DIRECT CURRENT (UHVDC) TRANSMISSION

Most long-distance HVDC transmission systems with power levels above 1000 MW are at a bipolar voltage level of ± 500 kV. Voltage level for the 2×3150 MW Itaipu HVDC transmission system in Brazil has been operating at ± 600 kV since the mid-1980s. Transmission voltages of ± 600 kV to ± 800 kV are classified as UHVDC. Higher-power transfers can be achieved over longer distances with lower losses by increasing the dc voltage level into the UHVDC range. A considerable body of work is ongoing in this area for potential applications in China, India, and North America. The controllability and the mechanical and electrical characteristics of UHVDC lines make them in many respects more favorable for long-distance bulk power transmission than UHVAC lines. Figures 15-37 to 15-39 and Table 15-3 compare differences between UHVAC and UHVDC transmission lines.

REFERENCES

- Adamson, C. and Hingorani, N.G.: *High Voltage Direct Current Power Transmission*. London, Garraway, 1960.
- Kimbark, E.W.: *Direct Current Transmission*. New York, Wiley-Interscience, 1971.
- Uhlmann, E.: *Power Transmission by Direct Current*. Berlin, Springer-Verlag, 1975.
- Carlsson, L. and Persson, A.: "New Technologies in HVDC Converter Design," *Proc. IEE Sixth International Conference on AC and DC Transmission*, April 29 – May 3, 1996, pp. 387–392.
- Jardini, J.A., Reis, L.B., Campos Barros, J.G., and Frontin, S.O.: "HVDC Transmission for Voltages above 600 kV: Evaluation of DC System and Converter Station Major Equipment," *Proc. IEEE/IREQ International Conf. on DC Power Transmission*, Montreal, 1984, pp. 71–78.
- Handbook for *Insulation Coordination of High Voltage DC Converter Stations*, EPRI Report EL5414, Electric Power Research Institute, Palo Alto, CA, 1987.
- Fletcher, D.E. and Patterson, N.A.: "The Equivalent Disturbing Current Method for DC Transmission Line Inductive Coordination Studies and DC Filter Performance Specification," *Proc. International Conf. on DC Power Transmission*, Montreal, Quebec, Canada, June 4–8, 1984, pp. 198–204.
- Zhang, W., Isalsson, A.J., and Ekstrom, A.: "Analysis on the Control Principle of the Active DC Filter in the Lindome Converter Station of the Konti-Skan HVDC Link," IEEE Paper No. PE-281-PWRS-0-06, 1997.
- Kanngiesser, K.W., Bowles, J.P., Ekstrom, A., Reeve, J. and Rumpf, E.: "HVDC Multiterminal Systems," *CIGRE* Paper 14-08, 1974.
- McCallum, D., Moreau, G., Primeau, J., Bahrman, M.P., Ekehov, B. and Soulier, D.: "Multiterminal Integration of the Nicolet Converter Station into the Quebec-New Enland Phase II HVDC Transmission System," *CIGRE Proceedings*, Paper 14-103, Paris, 1994.

- Bahrman, M.P., Larsen, E.V., Patel, H.S. and Piwko, R.J.: Experience with HVDC-Turbine-Generator Torsional Interaction at Square Butte," *IEEE Trans. Power Appar. Syst.*, Vol. PAS-99, May-June 1980, pp. 966-975.
- Lahtinen, M.: "Connection of Harmonic Producing Installations in AC High Voltage Networks with Particular Reference to HVDC: Guide for Limiting Interference Caused by Harmonic Currents with Special Attention for Telecommunications Systems," *Electra (CIGRE)*, No. 159, April 1995, pp. 26-48.
- Arkell, C.A., Larsen, K.B., Dellby, B. and Luoini, G.: "Comparison of AC and DC Underground and Submarine Cable Transmission Systems," *CIGRE Symposium S 09-87 on AC/DC Transmission Interactions and Comparisons*, Paper No. 500-02, Boston, 1987.
- HVDC Ground Electrode Design*, EPRI Research Project 1467-1, Report EL-2020, International Engineering Co., Inc.
- Asplund, G., Stromberg, H., Blidberg, I. Saksvik, O. and Loof, G.: "Outdoor Thyristor Valve for HVDC," *Proc. IEEE/Royal Institute of Technology Stockholm Power Tech: Power Electronics*, June 18-22, 1995.
- Krishnayya, P.C.S.: "Important Characteristics of Thyristors of Valves for HVDC and Static Var Compensators," *CIGRE Conf. Proc.*, Paper 14-10, 1984.
- Ekstrom, A. and Liss, G.: "A Refined HVDC Control System," *IEEE Trans. Power Systems*, Vol. 89, 1970, pp. 723-732.
- CIGRE Joint Working Group 13/14-08: "Circuit Breakers for Meshed Multiterminal HVDC Systems," Part I, "DC Side Substation Switching Under Normal and Fault Conditions," *Electra (CIGRE)*, No. 163, December 1995, pp. 98-122; Part II, "Switching of Transmission Lines in Meshed HVDC Systems," *Electra (CIGRE)*, No. 164, February 1996, pp. 63-82.
- Sakshaug, E.C., Kresge, J.S. and Miske, S.A.: "Arrester Protection of High Voltage DC Transmission System Converter Terminals," Paper No. 71TP47, PWR, Power Appar. Syst., Vol. PAS-90, No. 4, July-August 1971.
- CIGRE Working Group 14-05: "Guide for Planning DC Links Terminating at AC System Locations Having Low Short Circuit Capacities," Part I, "AC/DC Interaction Phenomena," *CIGRE Publication No. 68*, 1992.
- CIGRE SC 14: 186: "Economic Assessment of HVDC Links," *CIGRE Publ. 186*.
- Asplund, G., Eriksson, K., Jiang, H., Lindberg, J., Palsson, R. and Svensson, K.: "DC Transmission Based on Voltage Source Converters," *CIGRE*, Paris, 1998.
- Axelsson, U., Holm, A., Liljegren, C. Aberg, M., Eriksson, K. and Tollerz, O.: "The Gotland HVDC Light Project—Experience from Trial and Commercial Operation," *CIGRE Conf.*, Amsterdam, The Netherlands, June 18-21, 2001.
- Railing, B.D., Miller, J.J., Moreau, G., Bard, P., Ronstrom, L., Lindberg, J.: "Cross Sound Cable Project Second Generation VSC Technology for HVDC," *CIGRE*, Paris, France, 2004.
- Weimers, L.: "Bulk Power Transmission at Extra High Voltages. A Comparison between Transmission Lines for HVDC at Voltages above 600 kV DC and 800 kV AC," *CEPSI 2004*, Shanghai, China, Oct. 17-22, 2004.
- Karlsson, T., Liss, G.: "HVDC Transmission with Extremely Long DC Cables, Control Strategies," *IEEE/KTH Stockholm Power Tech Conf*, 1995, Paper SPT PE 01-05-0638.
- Carlsson, L., Flisberg, G.: "Recent Classic HVDC Development," *IEEE/PES T&D 2002 Latin American Conf.*, Sao Paulo, Brazil, March 18-22, 2002.
- Holmberg, P., Jonsson, T., Lagerkvist, M.: "Properties of Capacitor Commutated Converters in Long HVDC Cable Transmission," *EPE'97*, Trondheim, Norway.

